SCHOOL OF CIVIL ENGINEERING

INDIANA DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

INFORMATIONAL REPORT

JHRP-85-11

A ROUTINE MAINTENANCE AND PAVEMENT PERFORMANCE RELATIONSHIP MODEL FOR HIGHWAYS

T.F. Fwa
K.C. Sinha

PURDUE UNIVERSITY

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Informational Report

TO: H.L. Michael, Director
Joint Highway Research Project

July 2, 1985

FROM: K.C. Sinha, Research Engineer
Joint Highway Research Project

File: 3-4-42

Attached is an informational report entitled, "A Routine Maintenance and Pavement Performance Relationship Model for Highways". The research was conducted by T.F. Fwa under my direction for his doctoral program.

The report presents an explicit examination of the relationship between highway pavement routine maintenance and pavement performance. An aggregate damage approach was employed in the analysis of pavement performance and a methodology was developed based upon the serviceability performance concept. A quantitative measure for levels of pavement routine maintenance was proposed.

It is felt that the research work will provide useful information to the IDOH, particularly in the development of the Pavement Management System.

Respectfully submitted,

K.C. Sinha

K.C. Sinha
Research Engineer and
Professor of Civil Engineering

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ABSTRACT

Highway pavement maintenance and its management are areas of serious concern and study today. A topic that deserves a great deal of research effort is the development of the relationship between pavement routine maintenance and pavement performance.

This study was undertaken to investigate the feasibility of employing an aggregate performance/damage approach in the analysis of highway pavement performance. A methodology was developed based upon the serviceability performance concept first conceived at the AASHO Road Test completed in the early 1960s.

Several new concepts were introduced in the process of developing the aggregate performance approach methodology. A new parameter, PSI-ESAL loss, was defined as an aggregate representation of pavement damage. A concept of zero-maintenance performance curve was adopted

to account for the effects of routine maintenance work. This concept permitted an estimation of the actual total damage of a pavement.

A quantitative measure for levels of pavement routine maintenance was proposed. This quantitative measure, coupled with the PSI-ESAL loss representation of pavement damage, facilitated the establishment of a relationship between pavement performance and level of routine maintenance.

On the basis of the above theoretical framework, a procedure for allocating pavement maintenance and rehabilitation costs in a highway cost allocation analysis was developed. This procedure was successfully implemented in a full-scale highway cost allocation study at state level. A further development of the performance analysis concept involved a quantitative assessment of the effects of routine maintenance on pavement. A maintenance effectiveness index was defined which provided a means for quantitative evaluation of pavement maintenance work.

The aggregate performance approach proposed is simple in concept and easy to understand. The amount of data required is much less than that required by a disaggregate distress function approach. The amount of analysis effort involved is also reduced considerably.

CHAPTER 1

INTRODUCTION

1.1 Background

In the area of highway pavement cost allocation analysis, there is a long-existing problem which still remains unresolved today. This problem involves the determination of the relative proportions of traffic and environmental responsibilities in highway rehabilitation and maintenance expenditures. In recent years, the major effort of most state highway agencies have been shifted from building new highways and facilities to preserving and rehabilitating the existing system. A sound solution to the stated problem is therefore vital to arriving at an equitable and efficient allocation of pavement costs to highway users.

The usefulness of the knowledge of traffic and environmental effects on pavement performance is not limited to the field of highway cost allocation. A better understanding of these effects would have significant implication in pavement design, monitoring and evaluation technology. It would also provide additional information for pavement maintenance and rehabilitation decision making, which is an important process of a pavement management system.

The basic concept and methodology presented in this dissertation was originally developed for the 1983-84 Indiana Highway Cost Allocation Study [1] for allocating pavement maintenance and rehabilitation costs. There were a number of problems which the Indiana study team faced at the beginning phase of the study. Firstly, there was a lack of pavement damage data in terms of individual distress types. Secondly, time and budget constraints did not permit a full scale disaggregate distress function analysis for cost allocation. As a result, a meaningful analysis based upon consideration of individual distress types could not be carried out.

It became necessary that an alternative cost allocation methodology be developed for the type of data available in Indiana. A research was then initiated to investigate the possibility of employing the annual roughness data which were available for practically the entire state highway system of Indiana. This had led to the development of a performance-based approach which forms the theoretical framework for the analysis presented in this dissertation.

The situation in Indiana is not unique. Due to the limitation of manpower and funds, most states do not possess the capability of maintaining detailed records of pavement conditions in terms of individual distress types for the entire road network. On the other hand, the experience of several states (including Indiana [2], Utah [3], Kentucky [4] and West Virginia [5]) has indicated that performance information, such as serviceability, could be obtained on the entire network in a relatively short period of time, thus making periodic and timely evaluation possible. The development of a performance-based methodology for pavement deterioration analysis would further enhance the value and effectiveness of such a monitoring approach by providing additional information concerning pavement performance.

1.2 Purpose and Scope of Research

The basic goal of this research was to develop a performance analysis methodology to evaluate the effects of traffic and environmental factors on highway pavements. In order to satisfy the immediate need of highway cost allocation study, a major part of the research effort was directed toward developing a sound framework for attributing pavement maintenance and rehabilitation costs to different vehicle classes based upon the pavement deterioration imposed by each individual class of vehicle.

A meaningful objective of this effort was to illustrate, through the application of the performance-based methodology to a full-scale cost allocation study at state level, that such an approach would be a feasible cost-effective alternative to a much more elaborate disaggregate distress function approach [8].

In addition to deriving the relative effects of load-related and non-load-related factors on pavement deterioration, further research was conducted to investigate the effects of routine maintenance on pavement performance. It was an objective of this study to provide useful information, by means of performance analysis at both project and network levels, to assist highway agencies in making rehabilitation and routine maintenance decisions.

In the process of accomplishing these objectives, some important questions need to be resolved. First of all, some form of relationship between pavement performance and level of maintenance must be established. To achieve this, an appropriate quantitative measure of pavement performance was required. In addition, levels of maintenance had to be defined in a manner such that they could be related to routine maintenance costs. These requirements are delineated by the dotted lines in Figure 1.1.

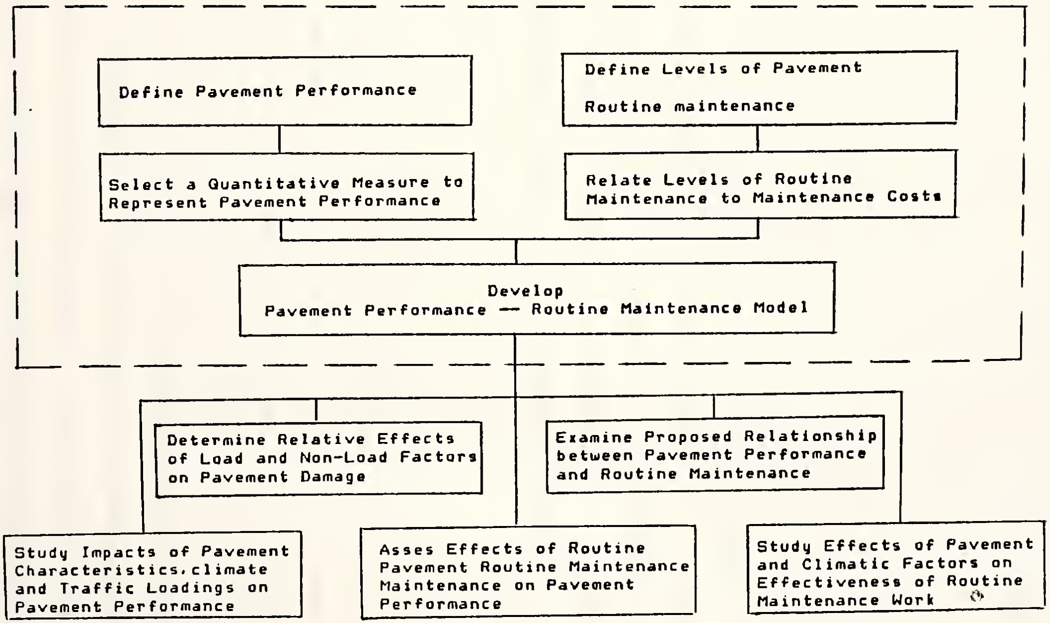


Figure 1.1 Major Work Items within Scope of Study

The performance-routine maintenance model in Figure 1.1 is the theoretical basis for all the analyses performed in this study. These analyses, as indicated in the figure, include (a) the determination of the relative effects of load and non-load factors on pavement damage for use in cost allocation; (b) the investigation of the effects of load and environmental factors on different pavement types, and the influence of pavement characteristics, climatic factors and subsoil conditions on the relative effects of load and non-load factors on pavement performance; (c) the examination of the relationship between pavement performance and routine maintenance assumed in the performance-routine maintenance model; (d) the evaluation of the effects of routine maintenance on pavement performance; and (e) the study of the effects of pavement, climatic and environmental factors on effectiveness of pavement routine maintenance work.

1.3 Dissertation Organization

The report consists of eight chapters covering two phases of the research. The research effort of Phase 1 focused primarily on developing the theoretical framework for the entire study. It involved the development of (a) the pavement performance-routine maintenance model depicted in Figure 1.1, and (b) a methodology to determine the relative effects of traffic and environmental factors on pavement deterioration. Detailed discussions of this theoretical framework are presented in Chapters 2 and 3.

Chapter 2 discusses differences between the commonly employed disaggregate distress function approach and the proposed aggregate performance approach for pavement damage analysis. A literature review on existing disaggregate distress function approach methodology is also presented in the same chapter.

Chapter 3 provides the theoretical basis of the proposed approach. The concept of PSI-ESAL loss as a measure of pavement deterioration is introduced, and the applicability of AASHO Road Test performance equations [9] to pavement deterioration analysis is examined. These are followed by a discussion of the need to consider effects of routine maintenance on pavement performance when performing a pavement deterioration analysis. Finally, the procedure of relating level of maintenance to performance, and the methodology of calculating the relative effects of load and non-load factors are presented.

In Phase 2 of the study, research was extended beyond the field of highway cost allocation to investigate the effects of traffic loadings, environmental factors, pavement characteristics and routine maintenance on pavement performance. These analyses were performed with data from the state highway system of Indiana. Chapter 4 gives an account of the type of data required, and how these data were collected, derived and used in the analyses.

The results of applying the aggregate performance approach methodology to the state highways of Indiana are analyzed in Chapters 5, 6 and 7. Chapter 5 investigates the impacts of pavement characteristics, climatic and subsoil conditions on the relative effects of load and non-load factors on pavement deterioration. In Chapter 6, the relationship between pavement performance and routine maintenance is examined. This is followed by Chapter 7 which presents an analysis of the influence of climatic and subsoil conditions on the effectiveness of routine maintenance.

Chapter 8 summarizes major findings of the study and indicates areas where further research is required.

CHAPTER 2

LITERATURE REVIEW:
DISAGGREGATE VERSUS AGGREGATE DAMAGE APPROACH

2.1 Introduction

Traditionally, there are two broad approaches in the evaluation of highway pavement conditions. One approach considers the gross performance of pavements by means of an aggregate measure. An example of this approach is represented by the AASHO Road Test concept of pavement serviceability [9, 10] which measures the ability at time of observation of a pavement to serve highway traffic. The other approach defines pavement conditions by specifying the extent and amount of individual pavement distresses. Examples of this approach are found in the pavement rating systems adopted by some state highway agencies [63,64,65,66].

In pavement damage responsibility analysis, where an estimate is made to assess the relative responsibility of load and environmental factors on pavement damage, the procedures used can likewise be classified into two approaches, namely the disaggregate distress function approach and the aggregate performance approach.

2.2 Relationship Between Disaggregate and Aggregate Damage Approach

The relationship between a disaggregate distress function approach and an aggregate performance approach for pavement damage analysis may be explained by considering the basic objectives of a pavement management system (PMS). Figure 2.1 shows a simplified flow diagram which outlines the sequence of testing involved in a typical pavement management system [6,7]. The system seeks to provide, among other information, answers to the following two questions: (i) where are the deficient sections requiring repair or improvement? (ii) what are the distress type involved in these deficient sections?

Two levels of condition survey may be identified in the PMS in Figure 2.1. They are labeled as levels I and II. Level I provides information to question (i), and level II to question (ii). The pavement damage analysis methodology described in this dissertation relies upon level I information only and is therefore termed an aggregate performance approach. Those methodologies that consider implication of individual distress types belong to methods of the disaggregate approach which requires detailed information from level II condition survey.

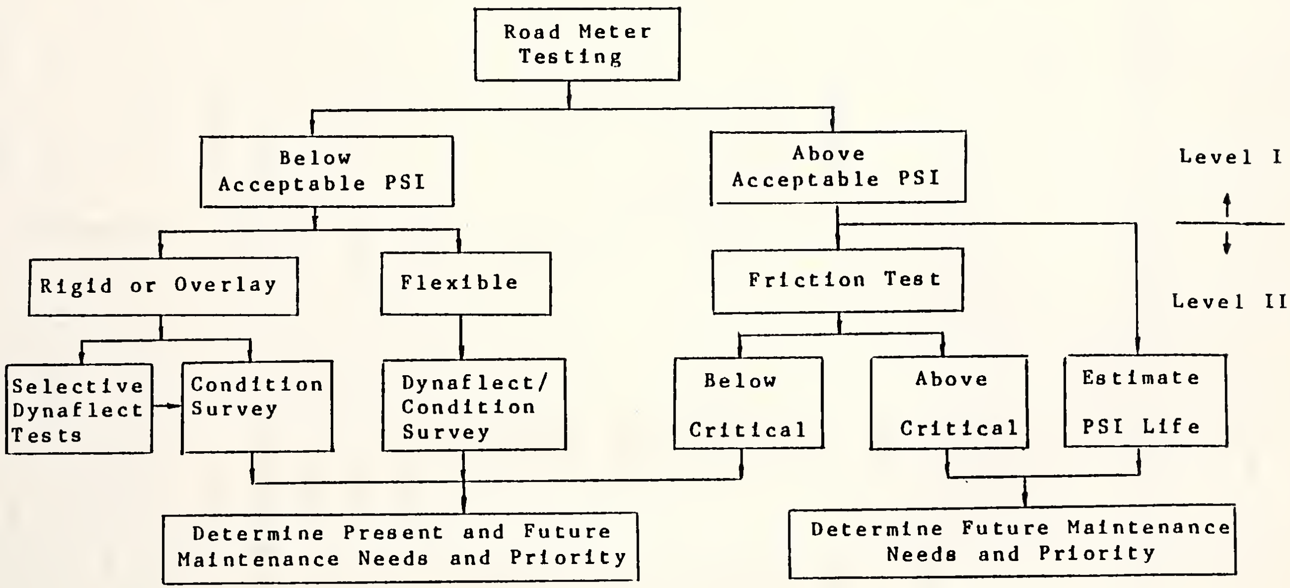


Figure 2.1 Sequence of Testing for a Pavement Management System

Besides the differences in the form of data required, the two approaches also differ significantly in the procedure by which pavement damage analysis is carried out. This is best illustrated by considering a highway cost allocation problem concerning pavement maintenance and rehabilitation costs.

Figure 2.2 indicates the major steps involved in a pavement maintenance and rehabilitation cost allocation analysis for both approaches. The sequence of analysis shown for disaggregate distress function approach is based upon the 1982 Federal cost allocation procedure [8], and that for aggregate performance approach based upon the procedure described in this dissertation.

A direct consequence of the difference in analysis procedure is apparent. The use of disaggregate distress function approach would require a large amount of data collection and handling effort. In contrast, the data required for an aggregate performance approach are much less and are more readily available.

2.3 Review of Disaggregate Distress Function Approach

2.3.1 1982 Federal Study

The 1982 Federal cost allocation study [8] was the first such study to employ consumption theory to assess analytically the pavement damage responsibilities of

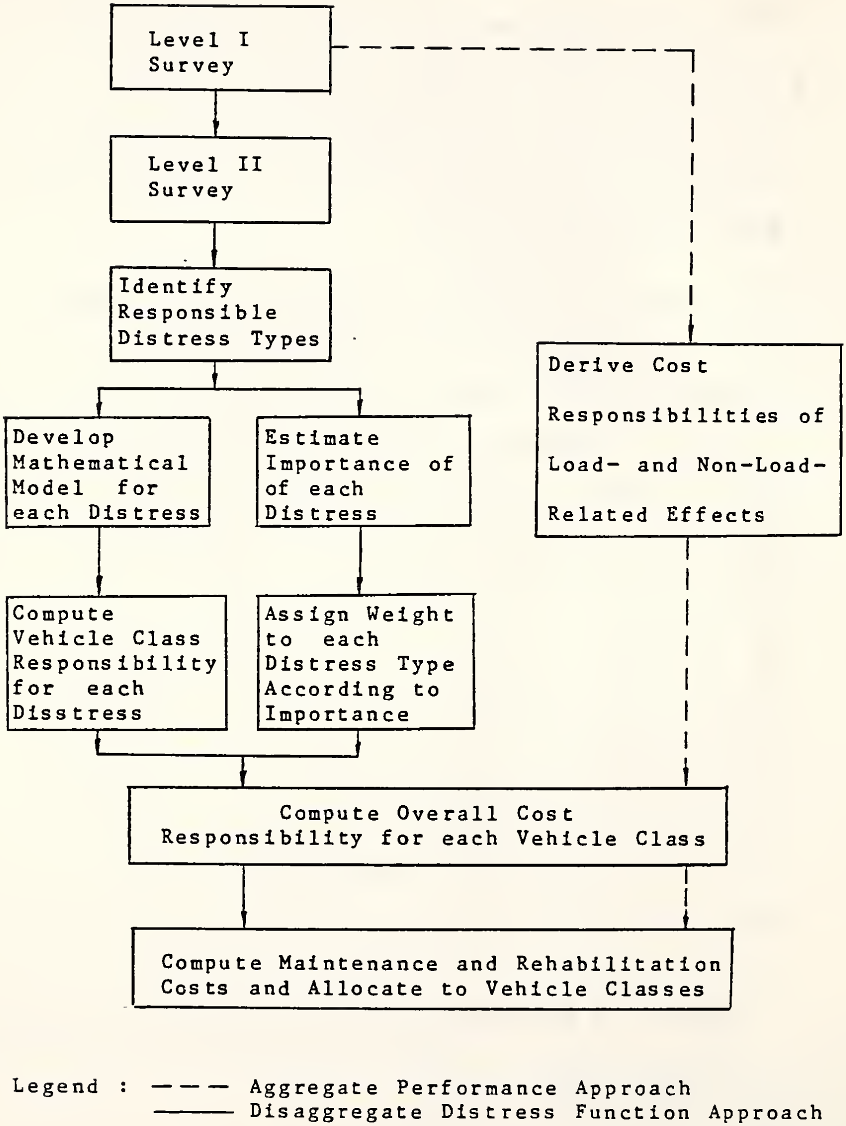


Figure 2.2 Sequence of Cost Allocation Analysis

vehicle classes. A consultant [11] was engaged specifically to develop pavement damage functions for cost allocation purpose. The analysis procedure of the approach has been outlined in Figure 2.2.

A list of distresses which were important to highway rehabilitation decision making was first identified. Mathematical models were then developed for individual distress types. To determine the pavement damage responsibilities of vehicle classes, it was necessary to calculate the responsibility of each vehicle class for each individual distress, and to estimate the relative importance of each distress in the decision to rehabilitate a given pavement.

The Federal methodology did not address the issue of load and environmental effects explicitly. To facilitate cost allocation computation, all mathematical damage functions of load-related distresses were modeled after AASHTO serviceability loss equations. Load equivalency factors for each distress type were developed for vehicle loadings to compute their relative responsibilities for the distress concerned. The models therefore did not provide any information on the relative pavement damage responsibilities of load and environmental factors.

Other limitations of the Federal approach include the following: (i) interaction of distresses was ignored; (ii) the effects of maintenance and maintenance policy were not considered; and (iii) maintenance costs, which represent a large percentage of total expenditures for most highway agencies at state and local levels, were not included in the analysis.

2.3.2 M.I.T. Pavement Life Cycle Cost Study

A recent research in the area of pavement damage responsibility analysis is a study carried out by Wong and Markow [10]. This was an extension of the Federal cost allocation study mandated by the Congress. The study focused on the allocation of life-cycle pavement costs, encompassing routine maintenance and rehabilitation, but excluding initial construction and reconstruction.

Central to this study was the use of an existing simulation model, known as the EAROMAR-2 system [12], to predict highway performance, maintenance and rehabilitation costs. An extensive amount of data was required as input to the model. The data included pavement structural and materials properties, existing pavement surface condition, traffic volume, composition and loading information, environmental conditions, maintenance policies, local practices of work scheduling, unit costs of maintenance labor, equipment and materials. The environmental factors considered were seasonal temperature, rainfall, freezing index, regional factors, and subgrade soil classifications.

The EAROMAR-2 system employed a series of pavement distress models to predict pavement damage. These models were based upon empirical pavement research or upon closed-form approximations to theoretical model predictions. The total cumulative damage of each distress type (or damage component) over the analysis period was computed by means of these predictive models. The Present Serviceability Index (PSI) of the pavement was then estimated as a function of the damage components.

It is unfortunate that the cost (or damage responsibility) allocation phase of the study was not treated with the same details and depth. Instead of examining individual distresses to assess the responsibility of each vehicle class, all damage responsibilities associated with load-related distresses were indifferently allocated on the basis of equivalent 18-kip single axle load (ESAL).

This limitation is not unexpected considering the fact that the EAROMAR-2 system was not originally developed for use in a cost allocation study. It is therefore not surprising that it did not provide the necessary information required for an equitable allocation of highway pavement costs.

It is appropriate at this point to state that, while many damage function models are available in the literature, there is hardly any theoretical model which could be used directly to compute the relative effects of load and environmental factors on pavement deterioration. Most models, being either regression based or empirical, cannot be used for such purpose.

2.3.3 1981 TTI Study

The 1981 TTI study [13] was conducted for the American Trucking Association and the Motor Vehicle Manufacturers Association. The procedure employed to estimate the proportion of pavement damage attributable to load involved the following steps: (i) classification of pavement distresses into 3 categories: load-related, environmental and combined stresses; (ii) determination of damage weighting factors for various distress types based upon pavement rating schemes; (iii) application of distress models to predict expected level of each distress; and (iv) combination of the weighting factors and predicted distress levels to determine the proportions of environmental and load-associated damage.

The assignment of distress type to a particular cause has a direct impact on the outcome of the final results. The assignment in TTI Study, unfortunately, was made largely by subjective reasoning. Another critical area of the study is the weighting of each distress type as to its relative importance to total pavement damage. As the TTI study found from a survey of pavement rating schemes from more than 40 states, "there exist a variety of practices from state to state, without a standard list of distresses that make up a pavement rating score, and without a standard weight applied to distress." This suggests that the use of subjective pavement rating schemes may not be a reliable means to assess the relative importance of different distresses.

The TTI study did not address the cost allocation phase of the problem. No attempt was made to estimate the shares of load and environment effects in combined distresses. Instead, upper and lower bounds of pavement damage responsibility of load effect were computed for different climatic zones. First, a total deduct point was established that would be subtracted from a perfect pavement rating score was evaluated for a given pavement. This total deduct point was computed by summing up the deduct points of 3 main categories, namely load, combined and climatic deduct points. The range of load damage responsibility was defined as follows:

Lower bound load damage ratio

$$= \frac{\text{Load deduct points}}{\text{Total deduct points}}$$

Upper bound load damage ratio

$$= \frac{\text{Load + Combined deduct points}}{\text{Total deduct points}}$$

The procedure depended heavily on pavement rating scheme which was directly related to decisions to rehabilitate or maintain. It is important to realize, however, that the problem of determining the relative effects of traffic loadings and environmental factors on pavement deterioration is not the same as the subject of decision criteria for maintenance and rehabilitation activities. Decision criteria are likely to vary among highway agencies that maintain and rehabilitate highway pavements. On the other hand, damage responsibilities of load and environmental factors are more a function of pavement characteristics, intensity of traffic loadings and severity of climatic conditions.

2.3.4 1981 Counsel Trans Study

Counsel Trans study [14] was also sponsored by the American Trucking Association and the Motor Vehicle Manufacturers Association. The pavement damage data used in the study were collected by windshield survey at around normal vehicle operating speed over a period of one and a half month. The survey covered 1187 miles of Interstate highways in six states, out of a total of over 40,000 miles nationally.

The study classified all distress types as either load related or environment related. The consequences of traffic loading on pavement already exhibiting environment related distresses, and the effects of environmental factors on pavement with load related distresses were not considered in the analysis.

In determining the relative damage responsibilities of load and environmental effects, a distress index was first computed for each distress type based upon the severity and extent of the distress. These indices were then grouped together without applying any weighting factors. This was equivalent to assigning equal weight to all distress types.

In general, the Counsel Trans approach is similar to TTI study in concept, but is less refined in many aspects. First of all, it is doubtful if windshield survey data are suitable for use at all in a scientific study such as this. The assumptions of non-existence of interaction of load and environmental effects, and of equal importance of all distress types greatly facilitated the data analysis in the study. The validity of these assumptions, however, are questionable.

2.4 Review Summary

The disaggregate distress function approach has a sound theoretical basis. However, due to the limitation of our present day knowledge on the subject of pavement distresses, and on the relationships between individual distresses and overall pavement performance, there are uncertainties involved in applying the concept to solving the problem concerning relative responsibilities of load and environment on pavement damage.

The review of existing disaggregate distress function approach procedures indicates that there are 3 major steps which are common to these procedures. These are: (i) identification of the distress types which affect pavement performance; (ii) development of distress models to determine load and environment responsibilities for each distress types; and (iii) assignment of weights to distress types based upon their relative importance to total pavement damage.

There exist two critical areas in the disaggregate approach that deserve attention. Different assumptions used in these two areas may significantly affect the final outcome of the analysis. Firstly, it is the identification of the causes of each distress (i.e., load versus non-load; or load-related, environment-related, and combination of load and environmental causes) and the subsequent form of distress function developed to model this distress. Secondly, it is the assignment of weighting factors to distress types according to their relative importance to pavement damage.

Each of the four studies [8,10,13,14] discussed in the preceding section adopted a different list of distress types which were considered to be important causes of pavement damage. All the four studies were also not agreeable upon whether a given distress type be classified as load-related, non-load-related, or combined effects of load and environment. Furthermore, as there is a large number of distress models available in the literature, it is not surprising that the distress functions employed in the four studies differ considerably in terms of the form of functional equation and the types of variable included.

The assignment of relative weights to different distress types has a direct impact on the computed magnitudes of the relative damage responsibility of load and environmental factors. Unfortunately, there does not exist a clear-cut objective way to determine the relative importance of each distress type. Since all the four studies adopted different weighting schemes in their analyses, there is a wide diversity of reported responsibility values for load and environmental effects.

In summary, it can be seen from the discussion above that although the disaggregate distress function approach is theoretically sound in concept, there can be considerable variations in the final results depending upon the type of distress considered, the form of distress models adopted, as well as the weighting scheme used to assign weights to distress types. This tends to suggest that, with the present state-of-art knowledge and technology in pavement condition monitoring and evaluation, an objective analytical solution which is acceptable and agreeable to all cannot be achieved by means of the disaggregate distress function approach.

CHAPTER 3

CONCEPTS OF PROPOSED AGGREGATE PERFORMANCE APPROACH

3.1 Introduction

The best known and most widely used aggregate pavement performance model is undoubtly the relationships between axle loadings and pavement deterioration developed through the AASHO Road Test of the early 1960s. These relationships have been summarized in the AASHTO Interim Guide for Design of Pavement Structures [9]. The present study adopted the AASHTO relationships as a measure of aggregate pavement performance. The general concept presented in this chapter, however, is still applicable should other measure of pavement performance be selected for use in analysis.

3.2 The Concept of PSI-ESAL Loss

A significant contribution of the AASHO Road Test was the introduction of pavement serviceability as a measure of pavement performance. It provided a means for quantitative evaluation of pavement condition and performance. This pavement evaluation procedure has gained widespread acceptance in pavement studies.

Pavement serviceability is usually expressed as an index number known as the Present Serviceability Index (PSI). The significance of the index is that it establishes relationships between objective pavement condition measurements and subjective ratings of road users. It is based upon the correlation of road user opinions with physical measurements of road roughness, cracking, patching and rutting.

The serviceability equations developed at the AASHO Road Test are shown in Equations (3.1) and (3.2).

For flexible pavements

$$PSI = 5.03 - 1.9 \log(1+SV) - 0.01\sqrt{C+P} - 1.33(RD)^2 \quad (3.1)$$

For rigid pavements

$$PSI = 5.41 - 1.80 \log(1+SV) - 0.09\sqrt{C+P} \quad (3.2)$$

where

$$SV = \frac{\sum_{i=1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2}{n-1} \quad (3.3)$$

SV = slope variance

x_i = the ith slope measurement

n = total number of slope measurements

C = linear feet of major cracking per 1000 sq.ft. of pavement area

P = bituminous patching in sq.ft. per 1000 sq.ft. of pavement area

RD = rut depth in inches in both wheel tracks measured with a 4-foot straightedge

It is important to note that PSI is a condition rating of a pavement at the time measurements are taken. No indication is given as to pavement characteristics, climatic, traffic and subgrade conditions, nor to the probable behavior of the pavement in the future. To evaluate pavement condition over a period of time, a performance history may be obtained by having serviceability measurements at different points of time in pavement life.

A typical pavement serviceability time history is shown in Figure 3.1 where PSI is plotted against pavement age in years. At any time t, the condition of the pavement is given by $(PSI)_t$, and the corresponding pavement deterioration is represented by a term known as serviceability loss, or PSI loss. The PSI loss at time t is equal to the difference between the initial PSI and the PSI at time t, that is,

$$\text{PSI loss at time } t = (PSI)_0 - (PSI)_t$$

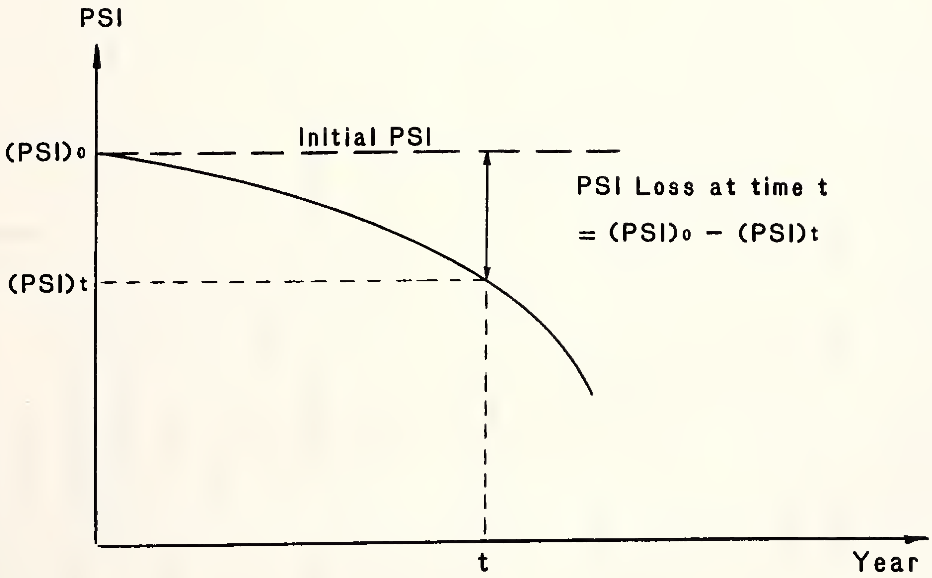


Figure 3.1 Pavement Serviceability Time History Plot

A more useful plot is obtained by plotting pavement serviceability against cumulative traffic loading expressed in terms of equivalent 18-kip single-axle loads (ESAL). A typical pavement serviceability-cumulative ESAL plot is shown in Figure 3.2. Such a plot is useful because it relates pavement performance to traffic loadings which are one of the major concerns of pavement engineers. More importantly, it permits a comparison to be made between measured field performance and AASHTO performance prediction, thereby allowing a pavement engineer to estimate, within reasonable limits, the performance trends of an in-service pavement.

Although PSI loss could still be used as an indication of the state of pavement deterioration at any given stage of pavement life as shown in Figure 3.2, it is not a convenient parameter for pavement performance analysis. This is because, as discussed earlier, the index PSI provides a condition rating of the pavement there and then, with no reference to influences of load and environmental factors. To overcome this problem, an alternative pavement deterioration measure is needed.

A new pavement deterioration measure was adopted for use in this research study for pavement performance analysis. This quantitative measure is represented by the shaded area in Figure 3.3. It is known as the PSI-ESAL loss of the pavement at the time of analysis, designated

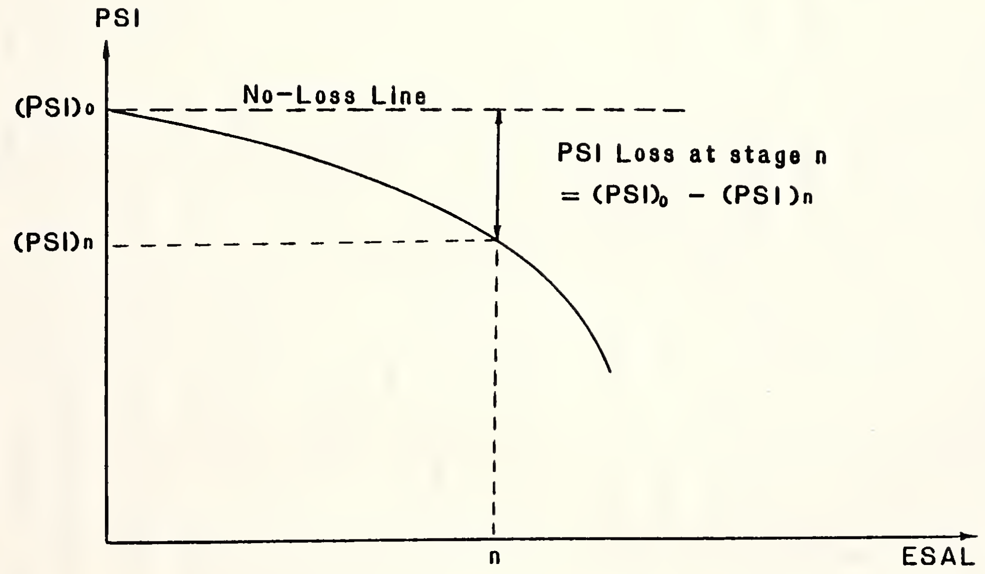


Figure 3.2 A Pavement Performance Plot in terms of Serviceability and Cumulative ESAL

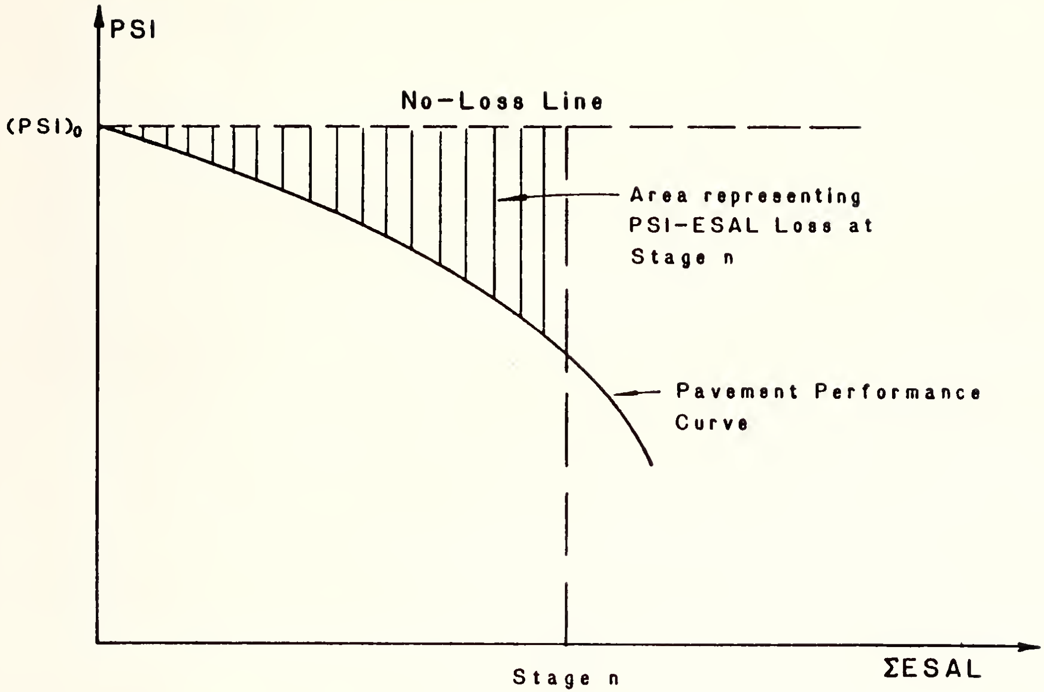


Figure 3.3 PSI-ESAL Loss as a Measure of Pavement Deterioration

as stage n in the figure. This new measure gives an additional dimension to the traditional measure, PSI loss. While PSI loss is an assessment of pavement condition at a point of time in pavement life, PSI-ESAL loss provides a measure of pavement deterioration covering the entire analysis period -- from the time the pavement is constructed, reconstructed, or resurfaced through the time of analysis.

On the understanding that pavement deterioration is the result of repetitive action of traffic loadings and cumulative effects of environmental factors, it is reckoned that PSI-ESAL loss provides a better representation of pavement deterioration for pavement performance analysis than the 'point-estimator' PSI-loss does. The use of PSI-ESAL loss greatly facilitates the incorporation of traffic loading and environmental effects into performance analysis because PSI-ESAL loss provides a means to measure pavement performance quantitatively on the same time frame basis as that used for evaluating loads and environmental effects. The research conducted in this study also found PSI-ESAL loss to be a convenient parameter for relating pavement performance to levels of routine maintenance, and for assessing the effectiveness of routine maintenance in repairing pavement damage.

3.3 Application of AASHO Road Test Results to Performance Analysis

3.3.1 AASHO Road Test Relationships

At the AASHO Road Test, pavement damage was defined in terms of PSI loss on a relative scale as follows:

$$G = \frac{P_0 - P}{P_0 - P_t}, \quad 0 < G < 1 \tag{3.4}$$

where

G = pavement damage measure

P_0 = initial serviceability index

P_t = terminal serviceability index

P = present serviceability index

This pavement damage measure was then related to load by means of regression analysis on the AASHO Road Test data. The general AASHO Road Test equation is [15]:

$$G = \left(\frac{W}{\rho}\right)^{\beta} \tag{3.5}$$

where

W = number of axle load applications

ρ = a constant equal to the number of load applications at which the damage G equals 1.0

β = a regression constant

To simplify the solution to equation (3.2.2) for mixed traffic, AASHO Road Test selected 18-kip single-axle load as a datum load level. By means of load equivalence factors (i.e. equivalent 18-kip single-axle load factor, or ESAL factor), all other axle loads were converted into ESALs for calculating the variable W in equation (3.5).

By definition, the ESAL factor of an axle load is the ratio of the number of load applications of the 18-kip datum load to cause a given level of damage to the number of load applications of the axle load under consideration to cause the same level of damage. It is important to note that ESAL factors vary with level of damage, with magnitude of axle load, with axle configuration, with pavement thickness, and with the stiffness of the subgrade.

3.3.2 AASHTO Performance Equations

Based upon the 1962 AASHO Road Test relationships between performance, pavement thickness and traffic loadings, the 1972 AASHTO Interim Guide [9] further extended these relationships to cover pavements built on different subgrade types.

For rigid pavements, modification of the general Road Test equation was accomplished by comparing stresses calculated from strain measurements on the Road Test pavement slabs with stresses calculated using the theoretical formula developed by Spangler [17].

For flexible pavements, a soil support scale was established based upon two types of roadbed support at the Road Test. A soil support value of 3.0 was assigned to the subgrade soil, and a value of 10.0 to the crushed-rock base material used. A linear scale between points 3.0 and 10.0 was assumed to incorporate the effects of soil support condition into the AASHO Road Test relationships. By checking the linear scale against a number of commonly used design procedures and against results of layered elastic theory analysis, it was found that the assumption of the linear soil support scale was reasonable.

The modified performance equations are:

For flexible pavements,

$$\log W = 9.36 \log(SN+1) - 0.20 + \frac{\log(G)}{0.40 + \dfrac{1094}{(SN+1)^{5.19}}} + 0.372\,(S - 3.0) \qquad (3.6)$$

For rigid pavements,

$$\log W = (4.22 - 0.32\,P_t) \log \left(\frac{M}{215.63J}\right) \frac{D^{0.75} - 1.132}{D^{0.75} - \dfrac{18.42}{Z^{0.25}}} + 7.35 \log(D+1) - 0.06 + \frac{\log(G)}{1 + \dfrac{1.624\times10^{7}}{(D+1)^{8.46}}} \qquad (3.7)$$

where

W = number of 18-kip single-axle load applications

SN = structural number

G = pavement damage defined in Equation (3.4)

S = soil support value

D = thickness of slab in inches

P_t = terminal serviceability index

M = modulus of rupture on concrete

J = load transfer coefficient

Z = E/k

E = Young's modulus of elasticity of concrete, psi

k = modulus of subgrade reaction, psi/in

Equations (3.6) and (3.7) are the performance equations used for the performance analysis described in this dissertation. It should be noted that the rigid pavement performance equation does not include any adjustment for environmental conditions different from the AASHO Road Test conditions. The reason stated was that it was not possible to measure the effect of variations in climatic conditions over the two-year life of the pavement at the Road Test site.

An adjustment was included for environmental conditions in flexible pavement performance equation presented in the AASHTO Interim Guide [9]. This adjustment was made by introducing a regional factor which takes a value of 1.0 for the AASHO Road Test site conditions. Unfortunately this factor cannot be clearly defined, and it has no direct relationship to any testing or measurement procedure. AASHTO Interim Guide mentioned that "there is no way to determine directly the regional factor for other locations and conditions". Van Til et al. [18] found from a survey of fifty states that one or more of the following were used by the states in assigning a regional factor:

1. Topography
2. Similarity to Road Test location
3. Rainfall
4. Frost penetration
5. Temperature
6. Groundwater table
7. Subgrade type
8. Engineering judgment
9. Type of highway facility
10. Substance drainage

Due to the uncertainty and subjective judgment involved in the determination of regional factors, this adjustment proposed by AASHTO was not adopted for use in this research, and it was not included in the performance equation (3.6). It is interesting however to note that by not making any adjustment for climatic conditions, the performance equations (3.6) and (3.7) can be used, as explained in the subsequent sections, as a reference for assessing the relative impacts of load and environmental effects on pavement damage.

3.3.3 Applicability of AASHO Road Test Results and AASHTO Performance Equations

The AASHO Road Test results and the AASHTO performance equations provide very useful relationships among pavement performance, structural thicknesses, traffic loadings and subsoil conditions. They have been used widely in the areas of pavement thickness design, pavement condition monitoring and evaluation. However, due to the limitation of the scope of the test and the conditions under which it was conducted, they cannot be applied in a straightforward manner in other areas. These areas include highway cost allocation study and performance analysis to determine the relative pavement damage responsibility of load and environmental factors.

The AASHO Road Test was conducted over a period of two years. This time period is relatively short compared to an expected service period of 20 years or more for most pavements. Furthermore, during the Road Test a maintenance policy was implemented to permit only minor maintenance so as to keep test traffic operating as much as possible [16]. In applying AASHO Road Test results to pavement performance analysis, one must therefore be aware of the following potential differences between AASHO Road

Test conditions and those of an actual pavement: (i) the level of maintenance performed; (ii) aging effects of pavement; and (iii) time period over which environmental factors are allowed to act.

3.3.4 Measure of Load Effects

ESAL may be considered to be a measure of the relative pavement damage responsibility of different traffic loadings under a reference set of conditions. These reference conditions represent those experienced or imposed at the AASHO Road Test. Based on the same reasoning, it may be said that the AASHTO performance equations could only account for the pavement damage that would have taken place under the reference conditions at AASHO Road Test.

In an ideal situation where (i) environmental conditions were the same as the reference conditions at AASHO Road Test, and (ii) pavement performance was explained exactly by the AASHTO performance equations, ESAL is the logical parameter for assigning damage responsibilities to various traffic loadings. This pavement deterioration, the responsibility of which could be meaningfully assigned to loads on the basis of ESAL, may be said to be caused by load-related effects.

The term load-related effects is used because there are no absolute measure of load effects. It is practically impossible to measure physically load induced damages without the influence of environmental factors. While the pavement damage explained by ESAL does involve the influence of environmental factors over the two-year period, it is believed that it offers the best measure of 'load effects' compared to other measures available in the literature.

3.3.5 Measures of Load-Related, Non-Load-Related, and Interaction Effects

Performance equations (3.6) and (3.7) were derived from results of the AASHO Road Test which was conducted in a single environment. For a pavement section experiencing more intensive environmental and pavement aging effects than those at the AASHO Road Test, a more severe deterioration could be expected as shown in Figure 3.4. Figure 3.5 shows the respective PSI-ESAL losses for AASHTO performance curve and the field performance curve of the pavement section at stage n. Area A gives the PSI-ESAL loss associated with AASHTO performance curve and area (A+B) the loss associated with field performance curve.

Two ratios may be computed from the PSI-ESAL losses in Figure 3.5: $a = \frac{A}{(A+B)}$, and $e = \frac{B}{(A+B)}$. Since area A represents the amount of pavement damage caused by the load-related effects defined in the preceding section,

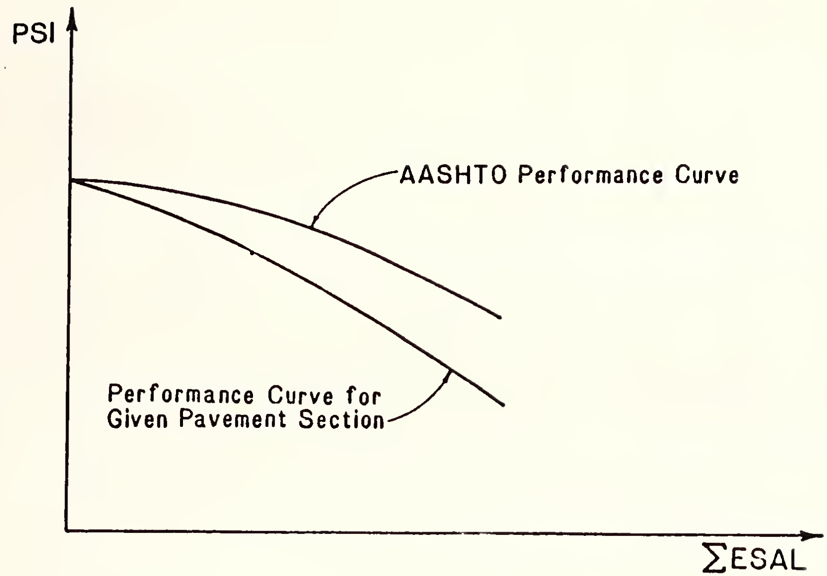


Figure 3.4 Schematic Diagram Showing Field and AASHTO Pavement Performance Curves

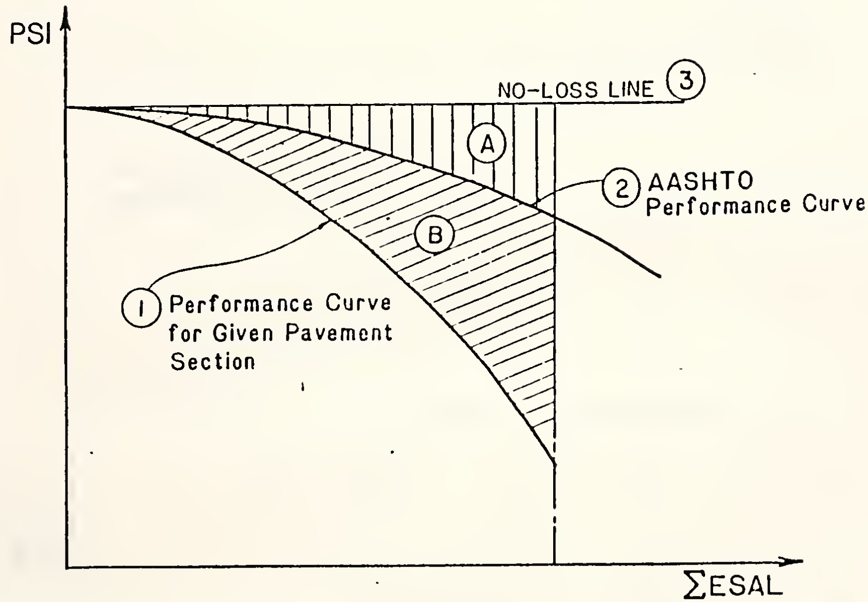


Figure 3.5 PSI-ESAL Losses for Field and AASHTO Pavement Performance Curves

area B may be taken to be further pavement damage caused by non-load-related factors and intersection of these factors with load-related factors. Accordingly, the ratio "a" represents the proportion of load-related effects, and "e" of non-load-related effects plus interaction of load-related and non-load-related effects.

3.4 Effects of Maintenance On Pavement Performance

3.4.1 The Need to Consider Effects of Routine Maintenance

The discussions presented in Section 3.2 does not mention about routine maintenance. There is however a need to consider the effects of routine maintenance in pavement performance analysis because observed or measured pavement damage is a result of combined effects of traffic loads, environment, age, initial design and construction, and past maintenance.

Referring to Figure 3.5 where curve 1 is the observed field performance curve and PSI loss (A+B) the associated pavement damage. It is very likely that the PSI loss (A+B) does not represent the true total pavement damage. This is because a certain level of routine maintenance is always present in practice. Some of the damages have already been repaired or ′recovered′ by maintenance work when a condition survey is made. This means that the true total pavement damage is greater than that represented by area (A+B) in Figure 3.5.

3.4.2 <u>The Concept of Zero-Maintenance Pavement Performance</u>

Theoretically, the true total damage for the pavement section considered in Figure 3.5 may be represented by the shaded area $(A+B)_0$ between curves 3 and 4 in Figure 3.6. Curve 3 is a hypothetical no-loss line and curve 4 a hypothetical performance curve for the pavement section in a situation where no maintenance has been carried out.

An actual pavement performance curve may lie anywhere between curves 3 and 4 depending upon the level of maintenance performed. The role of routine maintenance is to move actual pavement performance curve away from the zero-maintenance curve. The higher the level of routine maintenance performed, the closer the field performance curve would be to the no-loss line.

3.4.3 <u>Derivation of Total Pavement Damage</u>

Consider the performance curves for three sections of a given stretch of pavement with uniform pavement characteristics and traffic loading history, but each with a different level of routine maintenance. These performance curves are shown schematically in Figure 3.7

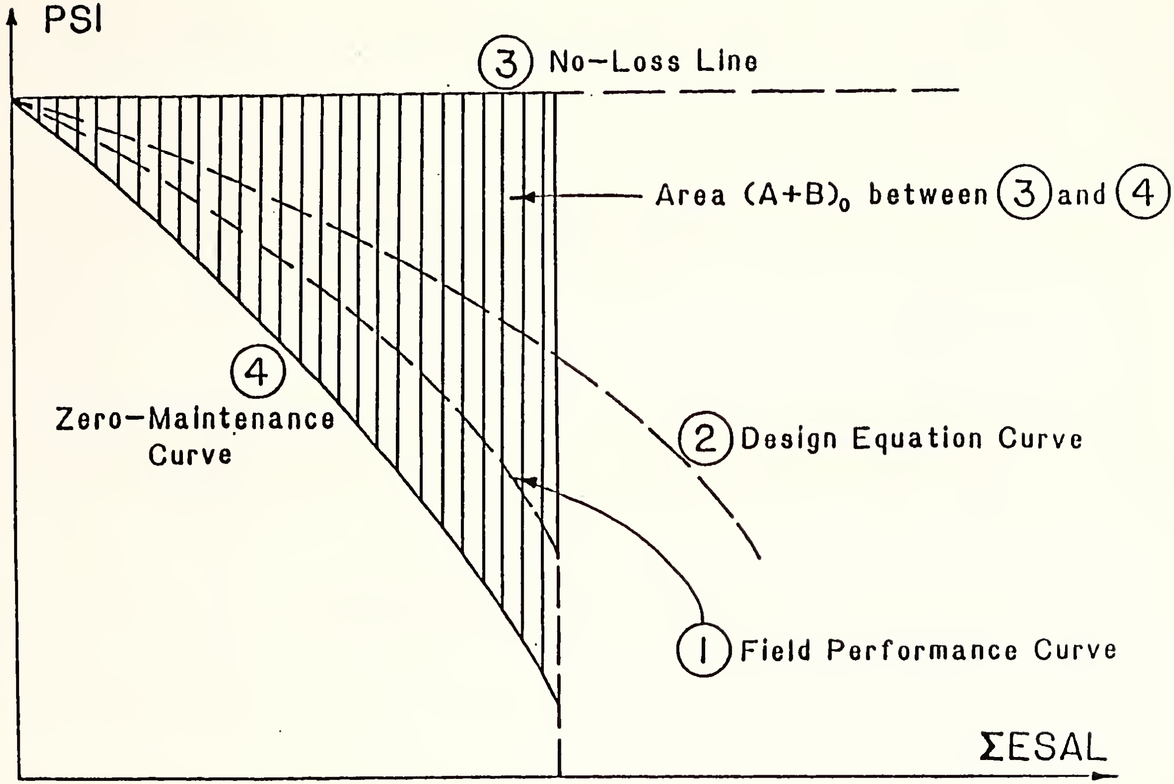


Figure 3.6 Total Pavement Damage as Defined by Zero-Maintenance Pavement Performance Curves

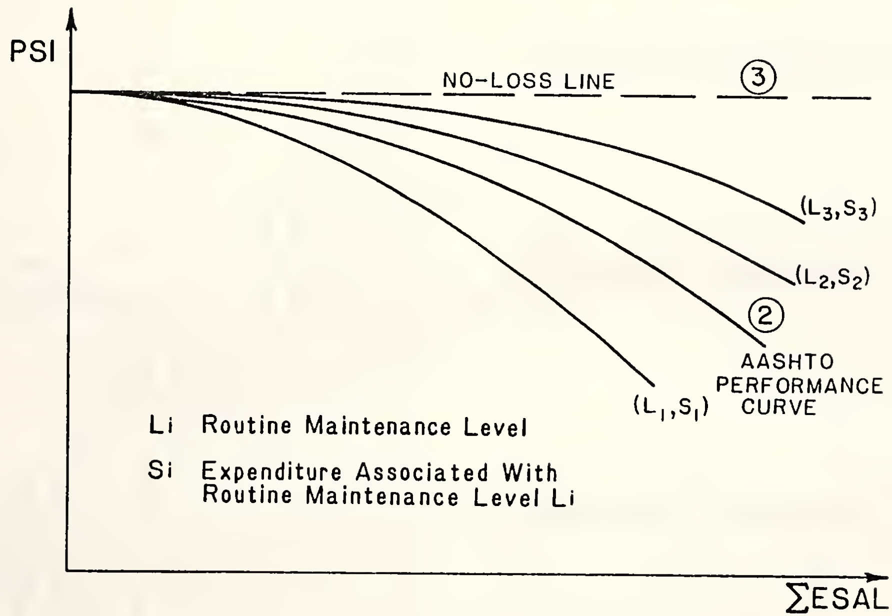


Figure 3.7 Schematic Diagram Showing Pavement Performance Curves with Different Levels of Routine Maintenance

in which maintenance level L_3 is higher than L_2, and L_2 higher than L_1.

Each of the three performance curves is also labeled with a value S_i which is the routine maintenance expenditure associated with maintenance level L_i. Assuming all three maintenance levels are performed with the same technology, it is reasonable to consider that the maintenance expenditure would be positively related to the level of maintenance performed. In Figure 3.7, one would expect S_3 to be greater than S_2, and S_2 greater than S_1. Routine maintenance expenditures can therefore be used as a meaningful indicator of the level of routine maintenance performed on a given pavement.

By plotting PSI-ESAL loss against a quantitative indicator of level of pavement routine maintenance, a relationship between pavement performance, expressed in terms of pavement damage, and routine maintenance may be derived by regression analysis or any other suitable procedure. This relationship may then be used to obtain the pavement damage at zero routine maintenance expenditure. This gives an estimate of the total pavement damage that would have occurred if no maintenance were to be performed on the pavement under consideration.

3.5 Determination of Load-Related and Non-Load-Related Effects by Proportionality Assumption

A schematic diagram representing the load-related and non-load-related effects responsible for pavement damage is shown in Figure 3.8(a). The proportions of these four effects in pavement damage are represented by a, b, c and d respectively in Figure 3.8(b). These four values add up to be 1.

$$a + b + c + d = 1 \tag{3.8}$$

Proportion "a" represents the load-related effects according to AASHTO design equations. It is given by:

$$a = \frac{A}{(A+B)_0} \tag{3.9}$$

Determination of $(A+B)_0$ has been described in the preceding section. Area A is computed from design equations for the same cumulative ESAL used in deriving area $(A+B)_0$.

Knowing proportion "a", it is possible to calculate proportions "b", "c" and "d" by making a proportionality assumption as follows:

$$\frac{b}{(b+c+d)} = \frac{a}{(a+b+c+d)} \tag{3.10}$$

$$\frac{c}{(a+b+c)} = \frac{d}{(a+b+c+d)} \tag{3.11}$$

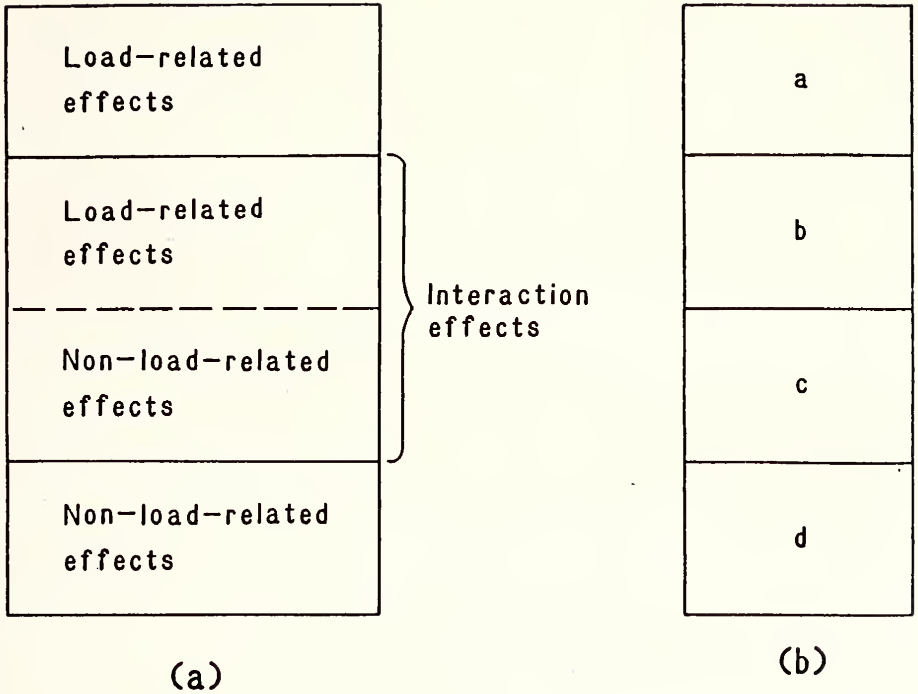


Figure 3.8 Schematic Diagram Showing Load-Related and Non-Load-Related Effects Responsible for Pavement Damage

Equation (3.10) assumes that for a given 'pure' load-related effects (proportion "a"), the share of load-related effects in the remaining non-load-related and interaction effects is directly proportional to the share of 'pure' load-related effects in the overall effects (a+b+c+d). Similarly, equation (3.11) assumes that for a given 'pure' non-load-related effects (proportion "d"), the share of non-load-related effects in the remaining load-related and interaction effects is directly proportional to the share of the 'pure' non-load-related effects in the overall effects (a+b+c+d).

In physical sense, the proportionality assumption implies that for a given pavement and a known set of environmental conditions and time period, the higher the traffic loading, the higher share it is going to have in the interaction effects. It also implies that for the same pavement with a given amount of traffic loading, the more severe the weather and other environmental conditions, the bigger is their share in the interaction effects. This phenomenon has been confirmed by the recent research of Sharaf [19]. Until further research indicates otherwise, these linear proportionality rules appear to be a reasonable first approximation.

Equations (3.10) and (3.11) may be reduced to:

$$b = a(b+c+d) \tag{3.12}$$

and

$$c = d(a+b+c) \tag{3.13}$$

Solving for "d" using equations (3.12) and (3.13), it gives

$$d = 1 - \sqrt{1 - (1-a)^2} \tag{3.14}$$

Proportions "b" and "c" may then be determined from solving equations (3.12) and (3.13). The total responsibility proportion of load-related effects is given by (a+b) and the total responsibility proportion of non-load-related effects by (c+d).

3.6 Summary of Proposed Approach

This section provides a summary to highlight the main features of the performance analysis concept presented. The entire approach is based upon the serviceability-performance concept developed at the AASHO Road Test. A new measure of pavement deterioration was proposed to replace the customarily adopted measure, PSI loss. The new measure, PSI-ESAL loss, provided a convenient parameter relating pavement performance to levels of routine maintenance, and to effects of traffic loadings and environmental factors.

The applicability of AASHO Road Test results and AASHTO performance equations to pavement performance analysis was examined in detail. The significance as well as the limitations of the Road Test results were highlighted and discussed. It was concluded that the AASHO Road Test results and the AASHTO performance equations could be used effectively for performance analysis of in-service pavements, provided that the effects of routine maintenance and environmental factors were properly accounted for.

The aggregate performance approach presented proposed to incorporate the effects of maintenance analysis by associating pavement performance with a level of routine maintenance. The level of routine maintenance of a given stretch of pavement was quantified by the maintenance expenditure spent to maintain the pavement.

The effects of environment on pavement deterioration was assessed by comparing actual pavement performance curves with the performance curves predicted by AASHTO performance equations. The concept of zero-maintenance performance curve was introduced for the purpose of estimating the actual total damage of a pavement. The PSI-ESAL loss associated with the zero-maintenance curve was derived by considering the relationship between actual pavement performance curves and their corresponding maintenance costs. The pavement damage represented by this zero-maintenance curve was taken as the total damage caused by the combined actions of all load and non-load factors.

Highway cost allocation analysis requires the knowledge of the relative responsibilities of load-related and non-load-related effects. A linear proportionality assumption was made to compute the corresponding pavement damage responsibility of the two effects. Further research is required to check the validity or reasonableness of this assumption.

CHAPTER 4

APPLICATION OF PROPOSED METHODOLOGY: PAVEMENT PERFORMANCE ANALYSIS OF INDIANA HIGHWAYS

4.1 Introduction

The aggregate performance approach developed in this research was employed to study the impacts of traffic loadings and environmental factors on Indiana State highway system as part of the 1983-84 Indiana Highway Cost Allocation Study [1]. This chapter discusses the types of data, and the procedure used in the study.

4.2 Data Requirement and Data Base Description

The 1983-84 Indiana Highway Cost Allocation Study provided a rare opportunity to test the validity of the proposed methodology with a full-scale analysis. The study dealt with the entire network of the state highway system in Indiana. A period of four years, 1980 to 1983, was selected as the study period for the analysis.

The data required for the analysis included the following main categories:

1. Pavement inventory data
2. Traffic data
3. Pavement performance data
4. Routine maintenance cost data
5. Subgrade soil data

4.2.1 Pavement Inventory Data

Pavement inventory data included the following sub-categories: pavement characteristic data, roadway geometry data and highway functional classification. The sources of these data are described below.

a. Pavement Characteristic Data -- Pavement type, age, and thickness information were contained in the Road Life Records and Construction Reports available at the Indiana Department of Highways (IDOH), and Construction Records prepared by the IDOH Division of Research and Training (DRT). Pavement type indicated whether the surface was flexible or rigid. Further information in the Road Life Records would reveal if a pavement was of composite nature with bituminous overlay on concrete slab. Pavement age refered to the length of time since the pavement was constructed. For flexible or overlay pavement, pavement age was referenced to the time the last resurfacing was carried out. Thicknesses and material types of bituminous layers of flexible pavements were available in the Construction Records as well as the Road Life Records.

b. Roadway Geometry Data -- Information such as roadway width, shoulder width and number of lanes was available in a number of sources, including the Road Life Inventory files maintained by the IDOH Planning Division, the Indiana HPMS records, the IDOH Road Life Records, and also the Construction Records of DTR for newly constructed pavements.

c. Highway Functional Classification -- The broad categories of highway classes adopted by the Indiana Highway Cost Allocation Study [1] were used. These were the Interstate highways, State Routes Primary and Secondary. This permitted direct use of the traffic data collected for the cost allocation study.

4.2.2 Traffic Data

Traffic data included traffic volume information, traffic stream composition, truck weight data, and vehicle axle configuration. In pavement performance analysis, these data were needed primarily for the purpose of computing traffic loadings in terms of ESALs.

a. Annual Average Daily Traffic (AADT) -- The annual average daily traffic volume in vehicles per day was obtained from the traffic maps published annually by the Planning Division, IDOH.

b. Accumulated Traffic Volume -- The accumulated traffic volume is the total number of vehicles that have traveled on a pavement over the entire analysis period. The analysis period was defined as the time period upto the end of 1983, computed from the time the facility was opened to traffic or the time the last major pavement rehabilitation was performed. The accumulated traffic volume was calculated from the following formula:

$$\text{Accumulated Traffic} = \sum_{i=1}^{n} \text{AADT}_i \times 365 \qquad (4.1)$$

where

ADDT_i = annual average daily traffic of the ith year taken from IDOH traffic maps

n = total number of years in analysis period

c. Vehicle Axle Configuration Classification -- Vehicles were grouped into fourteen classes, as shown in Table 4.1, according to their axle configurations. The axle configuration characteristics of the fourteen classes are shown in Figure 4.1. Each vehicle class was further divided into weight categories based upon

Table 4.1 Vehicle Classification for Performance Analysis

Class	Description
1	Small passenger cars
2	Standard and compact passenger cars, panel and pickup
3	Two-axle trucks (2S and 2D)
4	Bus
5	Cars with one-axle trailer
6	2S1 Tractor-trailers
7	2S1 Tractor-trailers
8	Cars with two-axle trailer
9	Four-axle single unit trucks
10	3S1 Tractor-trailers
11	2S2 Tractor-trailers
12	3S2 Tractor-trailers
13	Other five-axle tractor-trailers
14	Tractor-trailers with six or more axles

Vehicle Class	Axles Configuration	Total No. of Axles	Number of Single Axles	Number of Tandem Axles
1		2	2	
2		2	2	
3		2	2	
4		2	2	
5		3	3	
6		3	1	1
7		3	3	
8		4	4	
9		4	2	1
10		4	2	1
11		4	2	1
12		5	1	2
13		5	5	
14		6	4	1

Figure 4.1 Axle Configuration Characteristics of Vehicle Classes

their gross operating weights. The complete vehicle classification is shown in Table 4.2.

d. Traffic Stream Composition -- The Indiana cost allocation team conducted a vehicle classification field survey at 60 randomly selected sites throughout Indiana during the summer of 1983. The data collected were then converted to represent an average day of the year with factors developed from the FHWA report "Vehicle Classification Case Study" performed for the HPMS [20]. A detailed description of this procedure is found in the Indiana cost allocation methodology report [21]. A summary of the results is given in Table 4.3, 4.4 and 4.5 for Interstate, State Route Primary and State Route Secondary, respectively.

e. Vehicle Weight Data -- IDOH conducted a truck weight survey in every two years. Data on truck weights by truck type were collected at 28 permanent weigh stations [22]. The data recorded included truck type, axle spacing, axle weight and registration code. These data were combined with Indiana cost allocation survey data to arrive at the vehicle weight distribution shown in Table 4.6, 4.7 and 4.8.

Table 4.2 Vehicle Class Weight Group Classification

Veh Class	Sub-Group	Gross Operating Weight in Pounds
1	1	All weights
2	1	All weights
3	1	< 7,500
3	2	7,500 - 10,000
3	3	10,000 - 12,500
3	4	12,500 - 15,000
3	5	15,000 - 17,500
3	6	17,500 - 20,000
3	7	20,000 - 22,500
3	8	22,500 - 25,000
3	9	> 25,000
4	1	All weights
5	1	All weights
6	1	< 17,500
6	2	17,500 - 20,000
6	3	20,000 - 22,500
6	4	22,500 - 25,000
6	5	25,000 - 27,500
6	6	27,500 - 30,000
6	7	30,000 - 32,500
6	8	32,500 - 35,000
6	9	> 35,000
7	1	< 20,000
7	2	20,000 - 22,500
7	3	22,500 - 25,000
7	4	25,000 - 27,500
7	5	27,500 - 30,000
7	6	30,000 - 32,500
7	7	32,500 - 35,000
7	8	35,000 - 37,500
7	9	37,500 - 40,000
8	1	All weights
9	1	< 22,500
9	2	> 22,500
10	1	< 27,500
10	2	27,500 - 30,000
10	3	30,000 - 32,500
10	4	> 32,500
11	1	< 22,500
11	2	22,500 - 25,000
11	3	25,000 - 27,500
11	4	27,500 - 30,000
11	5	30,000 - 32,500
11	6	32,500 - 35,000
11	7	35,000 - 37,500
11	8	37,500 - 40,000
11	9	40,000 - 42,500
11	10	42,500 - 45,000
11	11	45,000 - 47,500
11	12	47,500 - 50,000
11	13	> 50,000
12	1	< 22,500
12	2	22,500 - 25,000
12	3	25,000 - 27,500
12	4	27,500 - 30,000
12	5	30,000 - 32,500
12	6	32,500 - 35,000
12	7	35,000 - 37,500
12	8	37,500 - 40,000
12	9	40,000 - 42,500
12	10	42,500 - 45,000
12	11	45,000 - 47,500
12	12	47,500 - 50,000
12	13	50,000 - 52,500
12	14	52,500 - 55,000
12	15	55,000 - 57,500
12	16	57,500 - 60,000
12	17	60,000 - 62,500
12	18	62,500 - 65,000
12	19	65,000 - 67,500
12	20	67,500 - 70,000
12	21	70,000 - 72,500
12	22	72,500 - 75,000
12	23	75,000 - 77,500
12	24	77,500 - 80,000
12	25	80,000 - 82,500
12	26	82,500 - 85,000
13	1	< 42,500
13	2	42,500 - 45,000
13	3	45,000 - 47,500
13	4	47,500 - 50,000
13	5	50,000 - 52,500
13	6	52,500 - 55,000
13	7	55,000 - 57,500
13	8	57,500 - 60,000
13	9	60,000 - 62,500
13	10	62,500 - 65,000
13	11	65,000 - 67,500
13	12	67,500 - 70,000
13	13	70,000 - 72,500
14	1	< 40,000
14	2	40,000 - 60,000
14	3	> 60,000

Table 4.3 Percent VMT of Vehicle Classes on Interstates

Veh Class	Sub-Group	Vehicle-Mile % Veh Class	Vehicle-Mile % Sub-Group
1	1	15.640	15.640
2	1	48.840	48.840
3	1	2.400	0.054
3	2		0.182
3	3		0.218
3	4		0.618
3	5		0.473
3	6		0.346
3	7		0.182
3	8		0.145
3	9		0.182
4	1	0.310	0.310
5	1	1.120	1.120
6	1	0.420	0.051
6	2		0.025
6	3		0.038
6	4		0.076
6	5		0.064
6	6		0.038
6	7		0.038
6	8		0.025
6	9		0.064
7	1	0.360	0.012
7	2		0.024
7	3		0.048
7	4		0.072
7	5		0.036
7	6		0.012
7	7		0.108
7	8		0.036
7	9		0.012
8	1	0.060	0.060
9	1	0.170	0.085
9	2		0.085
10	1	0.070	0.014
10	2		0.014
10	3		0.028
10	4		0.014
11	1	2.500	0.050
11	2		0.097
11	3		0.360
11	4		0.163
11	5		0.295
11	6		0.230
11	7		0.195
11	8		0.180
11	9		0.213
11	10		0.195
11	11		0.195
11	12		0.180
11	13		0.148
12	1	27.200	0.054
12	2		0.272
12	3		0.944
12	4		2.657
12	5		2.149
12	6		1.333
12	7		1.115
12	8		0.979
12	9		0.898
12	10		0.827
12	11		0.800
12	12		0.770
12	13		0.680
12	14		0.800
12	15		0.870
12	16		1.104
12	17		0.979
12	18		0.925
12	19		1.034
12	20		1.496
12	21		2.258
12	22		2.394
12	23		1.170
12	24		0.552
12	25		0.044
12	26		0.101
13	1	0.760	0.088
13	2		0.146
13	3		0.029
13	4		0.059
13	5		0.029
13	6		0.029
13	7		0.059
13	8		0.029
13	9		0.029
13	10		0.059
13	11		0.029
13	12		0.087
13	13		0.087
14	1	0.160	0.053
14	2		0.053
14	3		0.053

Table 4.4 Percent VMT of Vehicle Classes on State Primary

Veh Class	Sub-Group	Vehicle-Mile % Veh Class	Vehicle-Mile % Sub-Group
1	1	20.200	20.200
2	1	68.600	68.600
3	1	2.400	0.138
3	2		0.369
3	3		0.369
3	4		0.509
3	5		0.415
3	6		0.230
3	7		0.139
3	8		0.139
3	9		0.091
4	1	0.090	0.090
5	1	0.530	0.530
6	1	0.940	0.329
6	2		0.141
6	3		0.188
6	4		0.141
6	5		0.023
6	6		0.023
6	7		0.031
6	8		0.031
6	9		0.032
7	1	0.330	0.066
7	2		0.022
7	3		0.022
7	4		0.022
7	5		0.040
7	6		0.040
7	7		0.040
7	8		0.040
7	9		0.040
8	1	0.210	0.210
9	1	0.190	0.027
9	2		0.163
10	1	0.040	0.010
10	2		0.010
10	3		0.010
10	4		0.010
11	1	0.470	0.030
11	2		0.073
11	3		0.117
11	4		0.088
11	5		0.059
11	6		0.059
11	7		0.007
11	8		0.008
11	9		0.007
11	10		0.008
11	11		0.005
11	12		0.005
11	13		0.005
12	1	5.770	0.017
12	2		0.121
12	3		0.563
12	4		0.733
12	5		0.444
12	6		0.271
12	7		0.171
12	8		0.185
12	9		0.138
12	10		0.153
12	11		0.190
12	12		0.138
12	13		0.138
12	14		0.205
12	15		0.138
12	16		0.375
12	17		0.254
12	18		0.271
12	19		0.188
12	20		0.171
12	21		0.375
12	22		0.306
12	23		0.171
12	24		0.017
12	25		0.017
12	26		0.017
13	1	0.150	0.045
13	2		0.030
13	3		0.022
13	4		0.015
13	5		0.008
13	6		0.008
13	7		0.008
13	8		0.003
13	9		0.003
13	10		0.003
13	11		0.003
13	12		0.002
13	13		0.002
14	1	0.110	0.037
14	2		0.037
14	3		0.037

Table 4.5 Percent VMT of Vehicle Classes on State Secondary

Veh Class	Sub-Group	Vehicle-Mile % Veh Class	Vehicle-Mile % Sub-Group
1	1	20.200	20.200
2	1	71.750	71.750
3	1	3.300	0.906
3	2		0.323
3	3		0.906
3	4		0.518
3	5		0.129
3	6		0.323
3	7		0.129
3	8		0.033
3	9		0.033
4	1	0.060	0.060
5	1	0.490	0.490
6	1	0.520	0.182
6	2		0.130
6	3		0.052
6	4		0.052
6	5		0.013
6	6		0.013
6	7		0.013
6	8		0.013
6	9		0.052
7	1	0.270	0.034
7	2		0.034
7	3		0.034
7	4		0.034
7	5		0.027
7	6		0.027
7	7		0.027
7	8		0.027
7	9		0.027
8	1	0.210	0.210
9	1	0.030	0.004
9	2		0.026
10	1	0.060	0.015
10	2		0.015
10	3		0.015
10	4		0.015
11	1	0.460	0.063
11	2		0.063
11	3		0.084
11	4		0.042
11	5		0.021
11	6		0.084
11	7		0.021
11	8		0.021
11	9		0.011
11	10		0.011
11	11		0.011
11	12		0.011
11	13		0.021
12	1	2.500	0.018
12	2		0.035
12	3		0.104
12	4		0.470
12	5		0.104
12	6		0.190
12	7		0.018
12	8		0.070
12	9		0.156
12	10		0.140
12	11		0.035
12	12		0.052
12	13		0.070
12	14		0.052
12	15		0.052
12	16		0.035
12	17		0.052
12	18		0.190
12	19		0.087
12	20		0.155
12	21		0.190
12	22		0.104
12	23		0.104
12	24		0.013
12	25		0.002
12	26		0.002
13	1	0.090	0.027
13	2		0.027
13	3		0.018
13	4		0.009
13	5		0.009
13	6		0.
13	7		0.
13	8		0.
13	9		0.
13	10		0.
13	11		0.
13	12		0.
13	13		0.
14	1	0.060	0.020
14	2		0.020
14	3		0.020

Table 4.6 Percent Axle Weight Distribution of Vehicle Classes and Weight Groups on Interstates

Veh Class	Sub-Group	Axle Number 1	2	3	4	5
1	1	50	50			
2	1	50	50			
3	1	46	54			
3	2	41	59			
3	3	42	58			
3	4	42	58			
3	5	41	59			
3	6	40	60			
3	7	37	63			
3	8	45	55			
3	9	35	65			
4	1	40	60			
5	1	40	40	20		
6	1	48	52			
6	2	41	59			
6	3	41	59			
6	4	39	61			
6	5	41	59			
6	6	39	61			
6	7	36	64			
6	8	40	60			
6	9	36	64			
7	1	29	35	36		
7	2	31	36	33		
7	3	33	37	30		
7	4	32	39	29		
7	5	31	37	32		
7	6	19	42	39		
7	7	26	39	35		
7	8	25	38	37		
7	9	27	38	35		
8	1	40	40	10	10	
9	1	24	22	54		
9	2	28	24	49		
10	1	39	34	27		
10	2	34	42	24		
10	3	28	48	24		
10	4	33	43	24		
11	1	25	27	48		
11	2	31	33	36		
11	3	32	31	37		
11	4	29	30	41		
11	5	27	30	43		

Veh Class	Sub-Group	Axle Number 1	2	3	4	5
11	6	26	33	41		
11	7	25	32	43		
11	8	25	33	42		
11	9	23	34	43		
11	10	21	37	42		
11	11	20	36	44		
11	12	19	34	47		
11	13	17	37	46		
12	1	34	31	35		
12	2	33	39	28		
12	3	31	40	29		
12	4	30	41	29		
12	5	29	42	29		
12	6	27	43	30		
12	7	25	44	31		
12	8	24	44	32		
12	9	23	42	35		
12	10	22	44	34		
12	11	21	43	36		
12	12	20	44	36		
12	13	18	45	37		
12	14	17	45	38		
12	15	17	44	39		
12	16	17	43	40		
12	17	16	43	41		
12	18	16	44	40		
12	19	15	43	41		
12	20	14	43	43		
12	21	13	44	43		
12	22	13	44	43		
12	23	13	44	43		
12	24	13	44	43		
12	25	15	40	45		
12	26	12	41	47		
13	1	24	28	16	16	16
13	2	20	24	21	14	21
13	3	21	27	20	20	12
13	4	20	24	20	20	18
13	5	17	28	19	19	17
13	6	18	28	16	16	23
13	7	19	13	13	27	27
13	8	17	26	22	18	17
13	9	22	27	16	19	16
13	10	14	24	22	21	19
13	11	16	23	20	20	21
13	12	15	22	19	20	24
13	13	15	27	21	19	18
14	1	29	48	9	7	7
14	2	20	42	13	13	12
14	3	12	46	14	14	14

Table 4.7 Percent Axle Weight Distribution of Vehicle Classes and Weight Groups on State Primary

Veh Class	Sub-Group	Axle Number 1	2	3	4	5
1	1	50	50			
2	1	50	50			
3	1	45	55			
3	2	44	56			
3	3	42	58			
3	4	45	55			
3	5	41	59			
3	6	39	61			
3	7	33	67			
3	8	42	58			
3	9	40	60			
4	1	40	60			
5	1	40	40	20		
6	1	36	64			
6	2	43	57			
6	3	38	62			
6	4	42	58			
6	5	41	59			
6	6	39	61			
6	7	36	64			
6	8	40	60			
6	9	34	66			
7	1	35	41	24		
7	2	36	39	25		
7	3	30	39	31		
7	4	32	39	29		
7	5	31	37	32		
7	6	30	39	31		
7	7	26	39	35		
7	8	25	38	37		
7	9	27	38	35		
8	1	40	40	10	10	
9	1	26	20	54		
9	2	20	19	61		
10	1	39	34	27		
10	2	34	42	24		
10	3	28	48	24		
10	4	33	43	24		
11	1	29	34	37		
11	2	28	33	39		
11	3	32	34	34		
11	4	29	31	40		
11	5	31	36	33		
11	6	24	30	46		
11	7	25	32	43		
11	8	23	37	40		
11	9	23	34	43		
11	10	20	33	47		
11	11	22	37	41		
11	12	19	34	47		
11	13	17	37	46		
12	1	28	44	28		
12	2	32	42	26		
12	3	32	40	28		
12	4	30	41	29		
12	5	29	42	29		
12	6	26	42	32		
12	7	24	42	34		
12	8	25	42	33		
12	9	23	46	31		
12	10	21	48	31		
12	11	20	42	38		
12	12	21	46	33		
12	13	18	40	42		
12	14	18	44	38		
12	15	18	42	40		
12	16	16	43	41		
12	17	16	44	40		
12	18	15	44	41		
12	19	14	44	42		
12	20	15	45	40		
12	21	14	44	42		
12	22	14	44	42		
12	23	14	43	43		
12	24	13	43	44		
12	25	12	46	42		
12	26	12	41	47		
13	1	13	18	23	23	23
13	2	13	18	23	23	23
13	3	14	25	23	18	20
13	4	20	24	20	20	18
13	5	17	28	19	19	17
13	6	18	28	16	16	23
13	7	19	13	13	27	27
13	8	17	26	22	18	17
13	9	22	27	16	19	16
13	10	14	24	22	21	19
13	11	16	23	20	20	21
13	12	15	22	19	20	24
13	13	15	27	21	19	18
14	1	22	37	14	14	13
14	2	20	42	13	13	12
14	3	12	46	14	14	14

Table 4.8 Percent Axle Weight Distribution of Vehicle Classes and Weight Groups on State Secondary

Veh Class	Sub-Group	Axle Number 1	2	3	4	5
1	1	50	50			
2	1	50	50			
3	1	50	50			
3	2	44	56			
3	3	40	60			
3	4	38	62			
3	5	41	59			
3	6	38	62			
3	7	40	60			
3	8	42	58			
3	9	40	60			
4	1	40	60			
5	1	40	40	20		
6	1	39	61			
6	2	43	57			
6	3	38	62			
6	4	42	58			
6	5	41	59			
6	6	39	61			
6	7	36	64			
6	8	40	60			
6	9	34	66			
7	1	37	41	24		
7	2	40	37	23		
7	3	36	39	31		
7	4	32	39	29		
7	5	31	37	32		
7	6	30	39	31		
7	7	26	39	35		
7	8	25	38	37		
7	9	27	38	35		
8	1	40	40	10	10	
9	1	28	24	48		
9	2	28	24	48		
10	1	39	34	27		
10	2	34	42	24		
10	3	28	48	24		
10	4	33	43	24		
11	1	29	34	37		
11	2	28	33	39		
11	3	27	35	38		
11	4	36	29	35		
11	5	27	38	35		
11	6	24	30	46		
11	7	25	32	43		
11	8	23	37	40		
11	9	23	34	43		
11	10	24	40	36		
11	11	22	37	41		
11	12	19	34	47		
11	13	17	37	46		
12	1	28	44	28		
12	2	34	43	23		
12	3	29	42	29		
12	4	30	41	29		
12	5	28	41	31		
12	6	28	43	29		
12	7	25	39	36		
12	8	23	45	32		
12	9	22	43	35		
12	10	20	42	38		
12	11	18	48	34		
12	12	18	40	42		
12	13	17	42	41		
12	14	16	51	33		
12	15	12	47	41		
12	16	16	43	41		
12	17	16	43	41		
12	18	15	46	39		
12	19	14	45	41		
12	20	13	45	42		
12	21	13	43	44		
12	22	13	43	44		
12	23	13	44	43		
12	24	13	43	44		
12	25	12	46	42		
12	26	12	41	47		
13	1	24	28	16	16	16
13	2	24	28	16	16	16
13	3	24	28	16	16	16
13	4	20	24	20	20	18
13	5	17	28	19	19	17
13	6	18	28	16	16	23
13	7	19	13	13	27	27
13	8	17	26	22	18	17
13	9	22	27	16	19	16
13	10	14	24	22	21	19
13	11	16	23	20	20	21
13	12	15	22	19	20	24
13	13	15	27	21	19	18
14	1	22	37	14	14	13
14	2	20	42	13	13	12
14	3	20	42	13	13	12

4.2.3 Pavement Performance Data

Since early 1960s the Joint Highway Research Project at Purdue University has been actively engaged in developing techniques for measuring pavement condition utilizing roughness numbers [23,24,25]. In 1973, the Division of Research and Training of the then Indiana State Highway Commission purchased a PCA Roadmeter for pavement condition measurements.

Roughness measurements on Indiana highways was started in 1974, but limited to selected pavement sections and to measuring the smoothness of newly constructed or resurfaced pavements. Since 1976, this monitoring program was extended to cover most Interstate highways and some primary state routes.

A cooperative research program between the IDOH Division of Research and Training and Purdue University was undertaken in 1976 to develop a system for the evaluation of pavement conditions in Indiana. As a direct consequence of this study, IDOH began a systematic recording of pavement roughness for all state highways in 1979. Five years (1979 to 1983) of complete roughness records for state highways were available in computer files at IDOH Division of Research and Training.

The PCA roadmeter was developed by the Portland Cement Association in the early 1970s. It was based on the reasoning that road roughness should be measured in terms of the roughness felt by the vehicle occupants in order to provide a good correlation with PSI. The device was installed in a car which was driven at 50 MPH over the highway. The PCA roadmeter roughness number was computed as the square of the number of 1/8 inch movements of the car body with respect to the rear axle. The results were reported by mile and by contract number of the pavement section.

4.2.4 Routine Maintenance Cost Data

Pavement routine maintenance cost data were obtained from the work of Sharaf [19]. The IDOH maintained a detailed record of highway routine maintenance work which was compiled from actual field maintenance activities recorded on field crew day cards. The maintenance activities that are related to pavement are shown in Table 4.9.

The information on routine maintenance is recorded on the basis of a highway section. A highway section refers to the portion of a highway that lies within the boundaries of a county. For each highway section of a given route, the following information was summarized for each of the nine pavement maintenance activities:

1. Total production units

Table 4.9 Pavement Routine Maintenance Activities

Activity Name	IDOH Code	Production Unit
1. Shallow Patching	201	Ton of mix
2. Deep Patching	202	Tons of mix
3. Premix Leveling	203	Tons of Premix
4. Seal Coating	205	Lane-Miles
5. Sealing Longitudunal Cracks and Joints	206	Linear Miles
6. Sealing Cracks	207	Lane-Miles
7. Cutting Relief Joints	209	Linear Feet
8. Joint and Bump Burning	214	Bumps Removed
9. Others	219	Man-Hours

2. Total man-hours

3. Types and quantities of materials

These quantities were then multiplied by appropriate unit costs to arrive at the dollar value of maintenance activities performed on the highway section. The cost items considered were labor, materials, and the cost of motor fuel consumed by maintenance equipment fleet.

4.2.5 Subgrade Soil Data

Subgrade soil data were required to estimate the soil support value, S, in the flexible pavement performance equation (3.6), and the modulus of subgrade reaction, k, in the rigid pavement performance equation (3.7).

a. Soil Support Value (S) -- There is no standard soil testing procedure established to determine the soil support value of a subgrade. It is customarily estimated through a correlation with some measure of subgrade strength. The Joint Highway Research Project at Purdue conducted a study in 1950 in which the California Bearing Ratio (CBR) values for the major types of soils found in Indiana were determined. Colucci-Rios and Yoder [29] later correlated CBR and soil support values to arrive at the S values given in Table 4.10 for the various soil types. A soil map is presented in Figure 4.2 to show

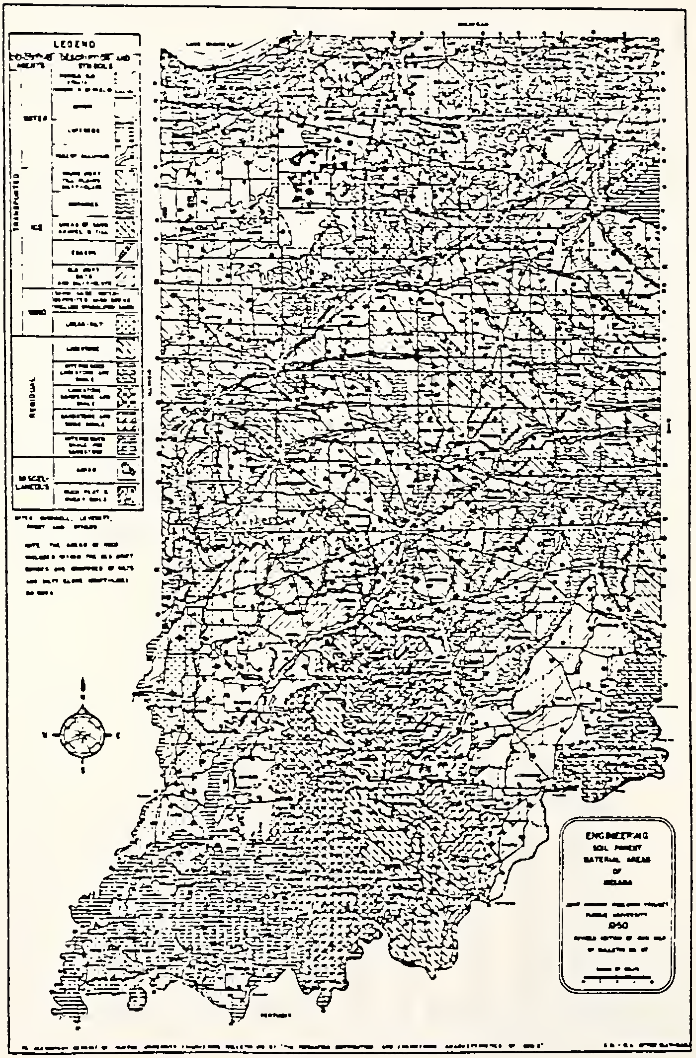


Figure 4.2 Engineering Soil Parent Material Distribution in Indiana

Table 4.10 Soil Support Values for Major Soil Types in Indiana

Soil Type			Soil Support Value
Water Transported	1.	Porous Substrata (Sands and Gravel)	6.8
	2.	Sands (except Kankakee Sands)	6.2
	3.	Kankakee Sands	5.6
	4.	Lakebeds	4.0
Ice Transported	5.	Young Drift Till Plains (Silty-Clays)	4.9
		Moraines	4.9
	6.	Areas of Sand, Gravel and Till Eskers	6.3
	7.	Old Drift, Silts and Silty-Clays	5.0
Wind Transported	8.	Sand : Some Water-Deposited Sand Areas	6.0
		Including Windblown Sands	6.0
	9.	Loess-Silts	5.3
Residual	10.	Limestone	4.9
		Interbedded Limestone and Shale	4.9
		Limestone, Sandstone and Shale	4.9
	11.	Sandstone and some Shale	5.1
		Interbedded Shale and Sandstone	5.1

the distribution of major soil types in Indiana. This map and the S values in Table 4.10 formed the basis for assigning soil support values to roadbed soil in this research study.

b. Modulus of Subgrade Reaction (k) -- This modulus represents the load in pounds per square inch on a loaded subgrade or subbase divided by the deflection in inches of that loaded area. AASHTO Interim Guide correlated k values with values obtained by plate loading tests using a 30-inch diameter plate. However, since plate loading tests are rarely performed in practice, the k values are usually estimated by correlation with other tests. This study followed the procedure adopted by Colucci-Rios and Yoder [29] by correlating k values with CBR based upon the relationship in Figure 4.3.

4.3 Determination of Field Performance Curves

Many state highway agencies maintain certain forms of pavement performance record as part of their pavement management or pavement evaluation system. In Indiana, as described earlier, the IDOH began to record roadmeter roughness measurements on state highway system in 1974. The use of roadmeter permitted the evaluation of a large mileage of pavements in a relatively short period of time. These pavement roughness measurements have been found to

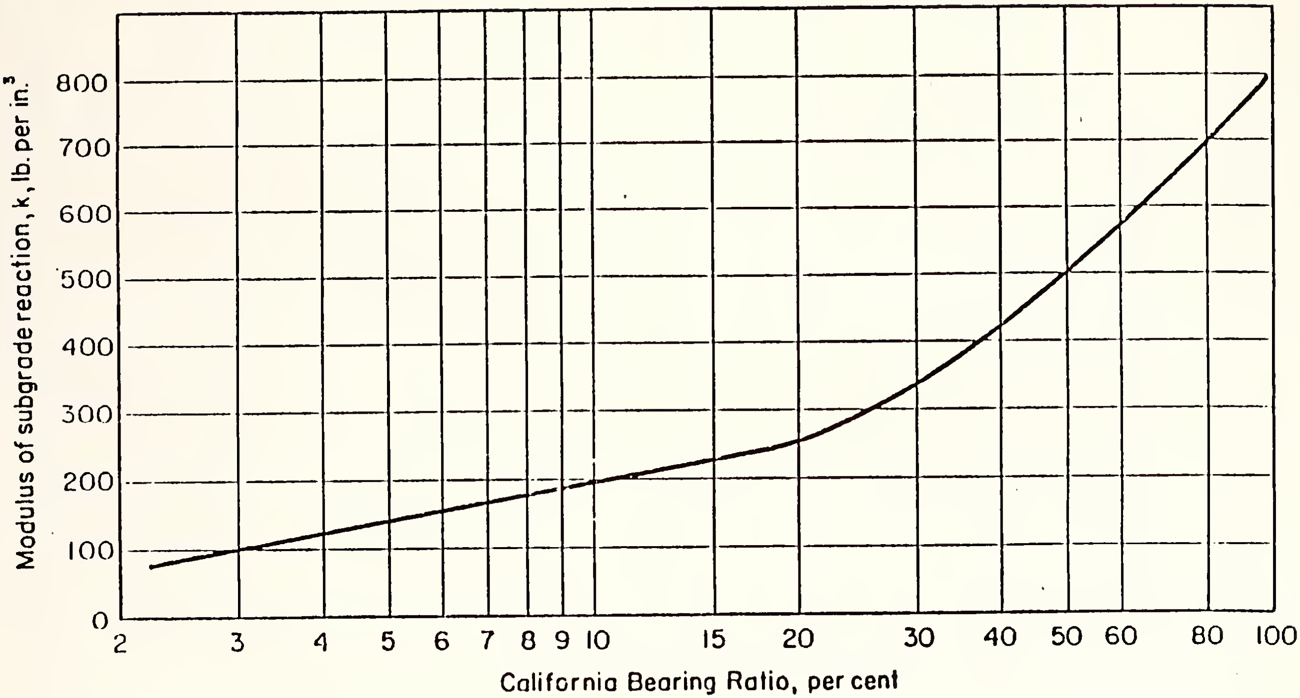


Figure 4.3 Relationship between California Bearing Ratio and Modulus of Subgrade Reaction

be an efficient means for screening highway pavements relative to their present serviceability [6].

4.3.1 Present Serviceability Index Model

Several present serviceability index (PSI) models have been developed for Indiana to correlate measured roughness and pavement serviceability. These models are presented in Table 4.11. Mohan's model [27] was the result of a two-year study on pavement serviceability performed at Purdue University. A study area with a radius of 70 miles was delineated around West Lafayette. A total of 94 sections, each 1 kilometer long, were randomly selected within the study area for serviceability studies.

A continuation of Mohan's study was conducted by Metwali [2]. A set of modified PSI models, which were simpler and give better correlation coefficients, was proposed. The study also produced some important conclusions with regard to measuring of pavement PSI. These are:

1. The seasonal effects on the measured roughness were non-significant for all pavement types included in the investigation.

2. One pass of the Roadmeter on the pavement concerned was sufficient for providing accurate results.

Table 4.11 Present Serviceability Index Models

(a) 1978 Mohan's Models [27]

Pavement	Model	R^2
Asphalt	$PSI = -9.2556 + 10.3244(\log C) - 2.048(\log C)^2$	0.78
Overlay	$PSI = 18.744 - 9.5708(\log C) + 1.423(\log C)^2$	0.70
JRC	$PSI = 8.0677 - 1.5387 * \log C$	0.57
CRC	$PSI = 4.9354 - 0.1274 * (\log C)^2$	0.46

Note : C = Roadmeter counts per kilometer

(b) 1981 Metwali's Models [2]

Pavement	Model	R^2
Asphalt	$PSI = 3.94 - 0.00072 * C$	0.79
Overlay	$PSI = 4.37 - 0.00174 * C$	0.77
JRC	$PSI = 4.69 - 0.00141 * C$	0.88
CRC	$PSI = 4.40 - 0.00070 * C$	0.59
JRC/CRC	$PSI = 4.58 - 0.00114 * C$	0.71

Note : C = Roadmeter counts per kilometer

(c) 1983 Division of Research and Training Models [28]

Pavement	Model	R^2
Flexible	$PSI = 8.72 - 1.96633 * \log(RN)$	0.71
Rigid	$PSI = 11.73 - 2.83369 * \log(RN)$	0.68

Note : RN = Roadmeter counts per mile

3. Measurements on two-lane highways showed non-significant differences between the two sides of the two-lane highways.

Based on the findings and recommendations of the two JHRP studies, a further study [28] was undertaken by the IDOH Division of Research and Training (DRT) to address some questionable areas found in the two studies. The number of test sections were increased to portray the current pavement makeup. Vehicles representative in kind and number of the traffic population were used and the roughness range was extended to cover the full range of roughness encountered in the field. Findings of the study include the following:

1. A linear model was suitable for a limited range of roughness numbers, but gave negative PSI value at higher roughness numbers.

2. Analyses showed that the response of CRC pavement was statistically similar to that of the JRCP sections. The same held true for flexible and overlay pavements.

The analysis performed in this dissertation adopted the 1983 DRT PSI models used by the IDOH Division of Research and Training in its pavement evaluation program.

4.3.2 Computation of Cumulative ESAL

The ESAL of each vehicle type was computed directly from the following equation which was developed from the AASHO Road Test [9,15]:

$$\log ESAL_x = g\left[\frac{1}{b_{18}} - \frac{1}{b_x}\right] + \log\left[\left(\frac{L_x + L}{19}\right)^A \Big/ (L)^B\right] \quad (4.2)$$

$$g = \log\left(\frac{I - P_t}{I - 1.5}\right) \quad (4.3)$$

$$b_x = C + \frac{D(L_x + L)^E}{(SN + 1)^F \ (L)^H} \quad (4.4)$$

$$SN = T \qquad \text{for rigid pavement} \quad (4.5)$$

$$SN = a_1D_1 + a_2D_2 + a_3D_3 \qquad \text{for flexible pavement} \quad (4.6)$$

where

$ESAL_x$ = equivalent single axle load of axle type x

L_x = axle load in kips

L = 1 for single axles

2 for tandem axles

P_t = terminal serviceability index

SN = slab thickness (rigid pavement)

structure number (flexible pavement)

A,B,C,D,E,F,H,I = constants with values specified in Table 4.12.

Table 4.12 Values of Constants in Equations (4.2) through (4.4)

Constant	Flexible Pavement	Rigid Pavement
A	4.79	4.62
B	4.33	3.28
C	0.40	1.00
D	0.081	3.63
E	3.23	5.20
F	5.19	8.46
H	3.23	3.52
I	4.20	4.50

a_1, a_2, a_3 = layer coefficients representative of surface, base and subbase course, respectively.

D_1, D_2, D_3 = thickness, in inches, of surface, base and subbase course, respectively.

In calculating ESAL with the above formulas, Indiana practice [38] was followed. A terminal serviceability index P_t value of 2.5 or 2.0 was used for flexible pavement, and 2.5 for rigid pavement. The following layer coefficients were used for computing flexible pavement structural number:

Bituminous Surface	= 0.4/inch
Bituminous Binder	= 0.34/inch
Bituminous Base	= 0.3/inch
Bituminous Stabilized Subbase	= 0.24/inch
Bituminous Aggregate Type "P"	= 0.14/inch
Granular Subbase	= 0.08/inch

Since the traffic stream composition on a given pavement section, and the accumulated traffic volume for the analysis period were known, the corresponding accumulated ESAL was computed as follows:

$$\text{Accumulated ESAL} = \sum_{i=1}^{N} P_i \times ESAL_i \times V \qquad (4.7)$$

where

N = total number of vehicle weight group type

P_i = proportion of vehicle type i in the traffic stream

$ESAL_i$ = ESAL of a single type i vehicle

V = accumulated traffic volume

4.3.3 Plotting of Field Performance Curves

For a given pavement section, knowing a PSI value and the corresponding cumulative ESAL, a point on the field performance curve of the pavement was obtained. This procedure was repeated for other points of time at which data were available. Field performance curve of the pavement was then plotted.

4.4 Procedure of Pavement Damage Responsibility Analysis

The IDOH pavement design method [26] follows the procedure described in the AASHTO Interim Guide [9]. IDOH uses a regional factor of 1.0 for all flexible pavements in the state. Equations (3.6) and (3.7) therefore represent exactly the design equations used in Indiana.

The major steps involved in the performance analysis of the state highway system of Indiana is discussed in the following sub-sections. The end results of this analysis give an estimate of the pavement damage responsibilities of load-related and non-load-related factors for each of the highway routes considered.

4.4.1 Criteria for Performance Analysis

At least two, desirably more, highway sections are required to establish the relationship between pavement performance and level of routine maintenance. Since the performance analysis is performed with reference to an AASHTO performance curve, it is valid only if all the highway sections included in each analysis have the same AASHTO performance curve.

As design criteria are different for different highway functional classes and types of pavement and pavement thicknesses, it is necessary to group pavements by highway class, pavement type and thickness, and to analyze them separately. Based upon the findings of the serviceability studies conducted by JHRP at Purdue University [2,27] and a study at IDOH Division of Research and Training [28], two pavement types were identified in this research. The two pavement types refer to flexible pavement and rigid pavement. Three highway classes were considered and they are Interstate highways, Primary and Secondary State Routes.

For flexible pavements, the AASHTO performance curve is given by Equation (3.6) and PSI values were computed by the flexible pavement PSI model in Table 4.11(c). For rigid pavements, Equation (3.7) and the rigid pavement PSI model in Table 4.11(c) were used.

The IDOH criterion [26] for selecting the terminal serviceability index, P_t, in Equation (3.4) was followed. For Interstate highways, Primary State Routes and some of the Secondary State Routes, a P_t value of 2.5 was used. For the remaining Secondary State Routes, the P_t value was set to 2.0.

4.4.2 Establishing No-Loss Line

The no-loss line shown in Figure 3.3 is defined by the initial PSI value of a pavement when it is open to traffic. For highways constructed or resurfaced after 1974, this information was available in the Construction Records maintained by the IDOH Division of Research and Training.

For pavement sections where the initial PSI was not recorded or not available, the following values were used: 4.20 for flexible pavements and 4.50 for rigid pavements. These are the values the AASHTO Interim Guide suggested for new pavements. They are also the values commonly used for computing serviceability loss in pavement evaluation practices [7,30].

4.4.3 Calculating PSI-ESAL Losses for Performance Curves

A computer program was written to compute, by means of numerical integration, the PSI-ESAL losses defined in

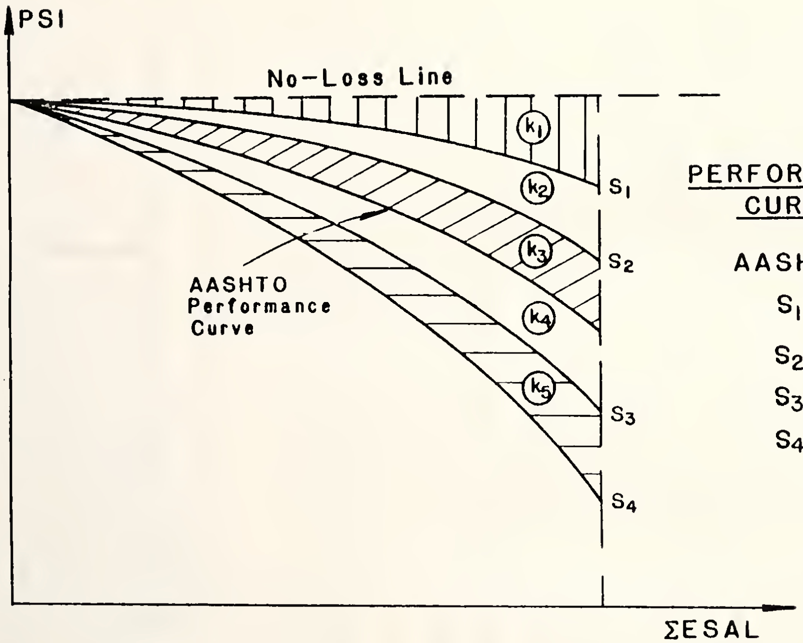
Figure 4.4. The AASHTO performance curve was defined by Equation (3.6) or (3.7), while the field performance curves were determined by the procedure described in Section 4.2.

4.4.4 Computing Routine Maintenance Expenditures

An aggregate annual pavement routine maintenance expenditure was first computed for each highway section by means of the procedure developed by Sharaf [19] described in Section 4.2.4. All costs were expressed in terms of 1983 dollars. An average annual maintenance cost was then calculated for the analysis period. The indicator chosen to represent a level of pavement maintenance of a highway section was the average annual dollar expenditure per lane-mile spent on the highway section. This index was obtained by dividing the annual pavement routine maintenance cost of the highway section by its total lane-miles.

4.4.5 Deriving PSI-ESAL Loss $(A+B)_o$ of Zero-Maintenance Curve

Each of the field performance curves in Figure 4.4 is defined by two parameters. The first parameter, PSI-ESAL loss $(A+B)_i$, represents the amount of observed pavement damage of highway section i, the second parameter, S_i, is the average annual dollar expenditure per lane-mile for



PERFORMANCE CURVE	PSI-ESAL Loss
AASHTO	$A = k_1 + k_2 + k_3$
S_1	$(A+B)_1 = k_1$
S_2	$(A+B)_2 = k_1 + k_2$
S_3	$(A+B)_3 = k_1 + k_2 + k_3 + k_4$
S_4	$(A+B)_4 = k_1 + k_2 + k_3 + k_4 + k_5$

Figure 4.4 Computation of PSI-ESAL Losses for Pavement Performance Curves

highway section i. It provides an indication of the level of pavement maintenance performed on the highway section.

To derive the PSI-ESAL loss $(A+B)_o$ of the so-called zero-maintenance curve, the PSI-ESAL losses (A+B) computed in Figure 4.4 were plotted against its respective level of maintenance represented by the expenditure parameter S_i. A least square line was fitted to the data points. The intercept of this line with the PSI-ESAL loss axis gives an estimate of the desired quantity $(A+B)_o$. An example of such a plot is shown in Figure 4.5.

4.4.6 Damage Responsibilities of Load-Related and Non-Load-Related Effects

Knowing PSI-ESAL loss A from Section 4.4.3 and $(A+B)_o$ from Section 4.4.5, Equations (3.9) through (3.14) were used to compute the relative pavement damage responsibilities of load-related and non-load-related effects.

For the example shown in Figure 4.5, area A for the pavement was computed to be 0.2163×10^7 PSI-ESAL. This gives a proportion "a" value of 0.4189. Solving Equations (3.12), (3.13) and (3.14), it gives

$$d = 0.1862$$

$$b = 0.2434$$

and $c = 0.1515$

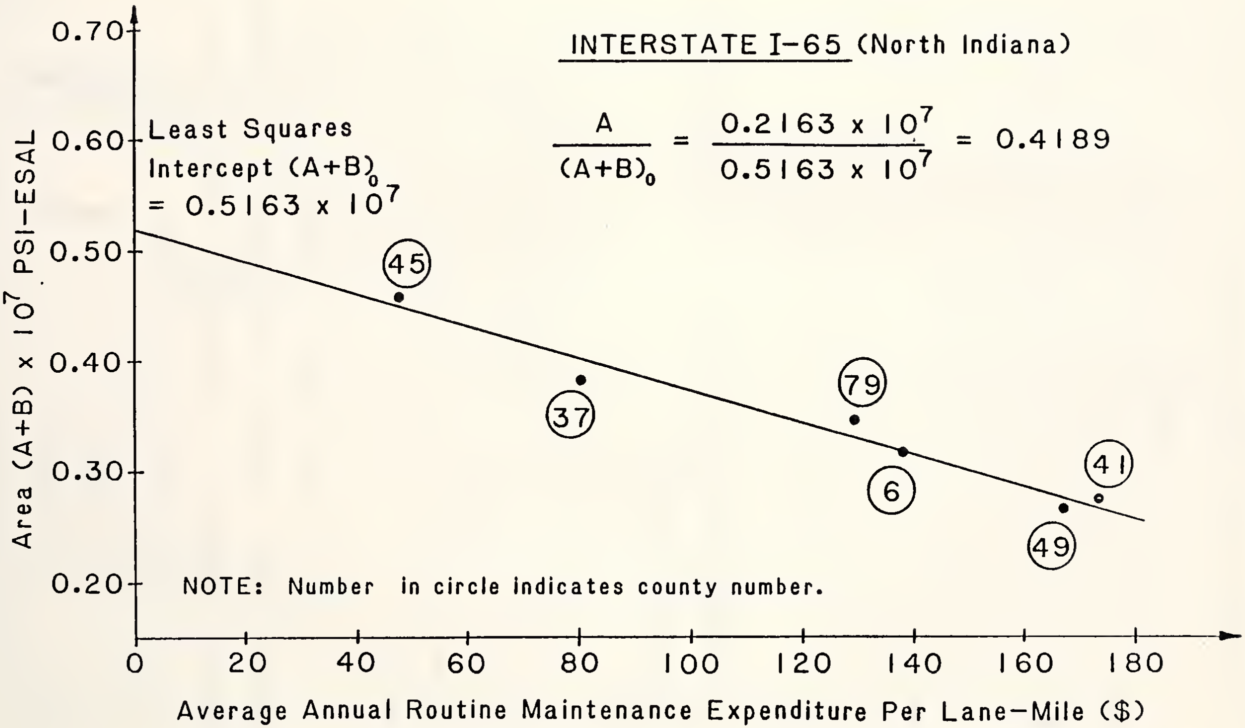


Figure 4.5 An Example of PSI-ESAL Loss (A+B) versus Routine Maintenance Plot

The total proportion of load-related effects therefore is $(a+b) = 0.6623$, and the total proportion of non-load-related effects is $(c+d) = 0.3377$.

CHAPTER 5

DAMAGE RESPONSIBILITIES OF LOAD-RELATED AND NON-LOAD-RELATED EFFECTS ON HIGHWAYS IN INDIANA

5.1 Introduction

This chapter presents the results of the application of the proposed aggregate performance approach to pavement damage responsibility analysis of the state highways of Indiana. Also included in this chapter are analyses performed to investigate the influence of pavement type, pavement thickness, climate, subsoil conditions and other factors on the relative magnitude of damage responsibilities of load-related and non-load-related effects. Further analysis of the results with respect to the relationship between pavement performance and routine maintenance is presented in Chapter 6.

5.2 General Description of the Results

A total of 75 cases were analyzed. These consist of 6 cases for rigid pavements and 69 cases for flexible pavements. Flexible pavements include asphalt pavements and composite pavements with bituminous overlay on concrete slab. Tables 5.1 and 5.2 provide a complete listing of the computed damage responsibilities for the 75 cases.

An effort was made to include as many highways as possible in the analysis in this study. There are in total eight Interstate highways in Indiana. Interstate 80/90 was not analyzed because it is a toll road, its maintenance cost data were kept separately from those of the state highway system and were not available for this study. An analysis of Interstate 465 was not possible as its entire length was located within one county, giving only one data point on a PSI-ESAL loss-maintenance expenditure plot.

By route number, there are about 195 state routes in Indiana. Many of these routes were not included in this study due to one or more of the following reasons: (i) the route consisted of one highway section only; (ii) maintenance cost data were not available; (iii) roughness data were not available; (iv) the pavement types of different highway sections were different; (v) the pavement thicknesses of different highway sections were different; or (vi) pavement characteristic data such as pavement thickness and age were absent.

In terms of highway number, 75% of Interstate

Table 5.1 Load-Related Pavement Damage Responsibilities for Flexible Pavements in Indiana

No	Highway Route	Percent Responsibility	No	Highway Route	Percent Responsibility
1	SR 1(n)	82.3	36	SR 39(n)	88.9
2	SR 1(s)	96.2	37	SR 39(s)	99.5
3	SR 2	71.3	38	US 40	89.6
4	SR 3(n)	89.5	39	US 41	98.6
5	SR 3(s)	95.1	40	SR 42	99.4
6	SR 4	83.2	41	SR 43(n)	92.9
7	SR 5	78.9	42	SR 43(s)	99.9
8	US 6	87.8	43	SR 44	95.4
9	SR 8	85.2	44	SR 46	94.1
10	SR 9(n)	87.8	45	SR 47	96.3
11	SR 9(s)	97.8	46	SR 48	94.5
12	SR 10	86.0	47	US 50	94.4
13	SR 13	83.4	48	US 52(n)	84.1
14	SR 14	86.4	49	US 52(s)	93.1
15	SR 16	93.8	50	SR 55	86.3
16	SR 17	86.0	51	SR 56	96.1
17	SR 18	88.2	52	SR 57	93.9
18	SR 19	88.2	53	SR 58	100.0
19	US 20	79.1	54	SR 60	94.6
20	SR 23	77.3	55	SR 62	96.9
21	US 24	87.7	56	SR 63	95.8
22	SR 25	86.8	57	SR 64	94.1
23	SR 26	92.0	58	I 64	97.1
24	SR 28	89.1	59	I 65(s)	100.0
25	SR 29	83.2	60	SR 67	91.4
26	US 30	82.9	61	SR 75	92.1
27	US 31(n)	82.0	62	SR 135	94.8
28	US 31(s)	82.9	63	US 150	94.6
29	SR 32	91.9	64	US 231(n)	89.6
30	SR 33	79.8	65	US 231(s)	90.6
31	US 35	89.0	66	SR 234	93.9
32	US 36	93.7	67	SR 236	90.5
33	SR 37(n)	82.5	68	US 421(n)	98.4
34	SR 37(s)	99.5	69	US 421(s)	96.9
35	SR 38	94.6			

Table 5.2 Load-Related Pavement Damage Responsibilities for Rigid Pavements in Indiana

Serial Number	Highway Route	Percent Responsibility
1	I-94	67.7
2	I-65	66.2
3	I-69	59.7
4	I-70	62.0
5	I-74	52.4
6	I-64	67.1

highways and about 30% of state routes are considered in the study. In terms of mileage, approximately 82% of Interstate highways and 61% of state routes are included.

All the 6 rigid pavement cases were found to be Interstate highways. The 69 flexible pavement cases included two Interstate highways which were the overlay pavement on the southern half of I-65 and the flexible pavement on part of I-64. The remaining 67 cases belonged to state routes. There were a few state routes which ran in the north-south direction across the state. These routes were divided into southern and northern halves based upon the reasoning that averaging effects of a combined analysis may conceal the influence of climatic effects which have been found to be statistically significant in two earlier studies [19,31].

5.3 Identification of Variables for Damage Responsibility Correlation Analysis

The factors that are likely to have an influence on the magnitude of the relative damage responsibilities of load-related and non-load-related effects are identified in this section. These factors may be classified into the following categories:

1. Pavement Characteristics

   Pavement type

   Pavement age

Pavement thickness

2. Traffic Loadings

Mean AADT

Mean annual ESAL

Accumulated ESAL

3. Environmental and Climatic Conditions

Freezing index

Mean annual snowfall

Mean annual rainfall

Thornthwaite moisture index

Freeze-thaw cycle index

Annual average temperature

Soil support value

The ranges of the values of these variable used in this study are summarized in Table 5.3.

5.3.1 Pavement Characteristics

a. Pavement Type --Damage responsibilities were computed for two basic types of pavements, namely flexible and rigid pavements. In this study flexible pavements included all types of asphalt pavements as well as composite pavements with bituminous overlay. Rigid pavements represented continuously reinforced concrete pavements, jointed reinforced concrete pavements and jointed plain concrete pavements.

Table 5.3 Ranges of Independent Variables in Statistical Analysis of Damage Responsibility Results

Variables		Rigid Pavement		Flexible Pavement	
		Minimum	Maximum	Minimum	Maximum
X2	Pavement Age (Years)	13.43	20.18	3.82	16.18
X3	Pavement Thickness (*)	10.00	10.00	4.23	6.21
X4	Mean AADT	10,516	50,099	332	11,994
X5	Mean Annual ESAL	465,000	2,215,000	2,240	455,000
X6	Freezing Index (^{o}F-Day)	0	536	0	559
X7	Mean Annual Snowfall (in.)	14.37	42.20	14.13	42.86
X8	Mean Annual Rainfall (in.)	36.31	43.88	36.20	43.99
X9	Thornthwaite Moisture Index	40.00	52.80	40.00	53.01
X10	Freeze-Thaw Cycle Index	110	120	110	161
X11	Annual Mean Temperature (^{o}F)	5.083	56.21	50.76	56.29
X12	Soil Support Value	4.90	6.80	4.50	6.80
X25	Cumulative ESAL	6,320,000	32,870,000	17,500	2,660,000

(*) Inches for rigid pavement
Structural number for flexible pavement

b. Pavement Age -- Different sections of a highway route may not have the same pavement age. To overcome this problem, a weighted average value was used in performance analysis to compute pavement damage responsibilities. This number was obtained by weighting the pavement age of each highway section with its length.

c. Pavement Thickness -- All the rigid pavements analyzed have the same thickness of 10 inches. A relatively wide range of pavement thickness, expressed in terms of structural numbers, is found in the case of flexible pavement as shown in Table 5.3.

5.3.2 Traffic Loadings

a. Mean AADT -- For each highway section, an arithmetic average AADT was first computed for the analysis period. These values for highway sections were then weighted by their respective lengths to yield the mean AADT for the highway route over the analysis period. It should be noted that the AADT values given in Table 5.3 refer to the AADT per lane. For undivided two-lane highways, directional split of 50-50% was applied to the total AADT values for the highway. This is in agreement with the design procedure of IDOH [26], and other commonly adopted practices [42,44,45]. For divided highways with two or more lanes, IDOH adopts the following lane traffic factors:

2 lanes each direction	0.9
3 lanes each direction	0.8

These factors were used in this study to compute lane AADT for performance analysis. These values are also recommended in other studies and practices [46,47,48]. The above procedure for computing lane AADT concurs with the findings and roughness measurement procedure in Mohan's [2], Metawali's [27] and the DRT [28] serviceability studies.

b. Mean Annual ESAL -- The arithmetic average annual cumulated ESAL value of each highway section was used to compute the desired mean annual ESAL value the entire highway route concerned, following the same weighting procedure used for calculating mean AADT described earlier. As short-cut methods for converting mixed traffic to ESAL, such as the use of an aggregate ESAL factor [50], are known to be the source of errors in pavement design and pavement analysis [18,51], ESAL values were computed for each pavement section using the original AASHTO formulas given in Equations (4.2) through (4.6).

c. Accumulated ESAL -- For a highway route, the analysis period was equal to the pavement age computed in Section 5.3.1. For each highway section on the highway route, an accumulated ESAL was calculated for the analysis period. The accumulated ESAL for the entire highway route was obtained by weighting each highway section accumulated ESAL value with its length.

5.3.3 Environmental and Climatic Conditions

a. Freezing Index -- Frost action of roadbed soil has long been recognized as a major factor which affects pavement performance [33,34]. Soil freezing depends to a large degree upon the duration of depressed air temperatures. Degree day has been used customarily to provide a measure of this effect. One degree day represents one day with a mean air temperature one degree below freezing. The freezing index for a given year is obtained from a cumulative plot of degree days versus time. It is equal to the difference between the maximum and minimum points on the cumulative degree-day plot. The freezing index has been correlated with depth of frost penetration in literature [30,32]. A map of mean freezing index distribution in Indiana is given in Figure 5.1.

b. Mean Annual Snowfall -- Based upon the Indiana snowfall records which are available at the Department of Agricultural Statistics, Purdue

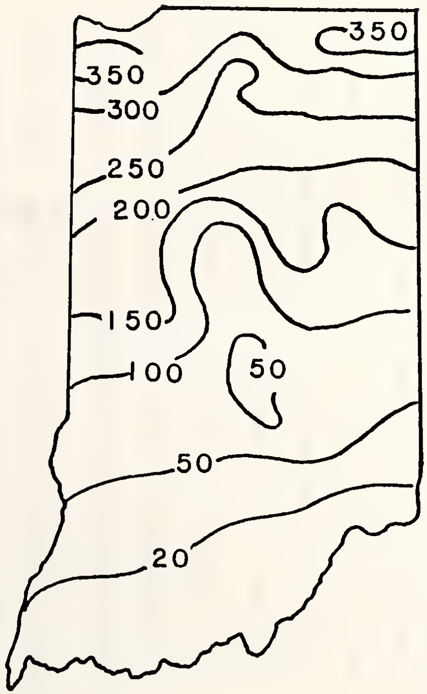


Figure 5.1 Distribution of Mean Freezing Index

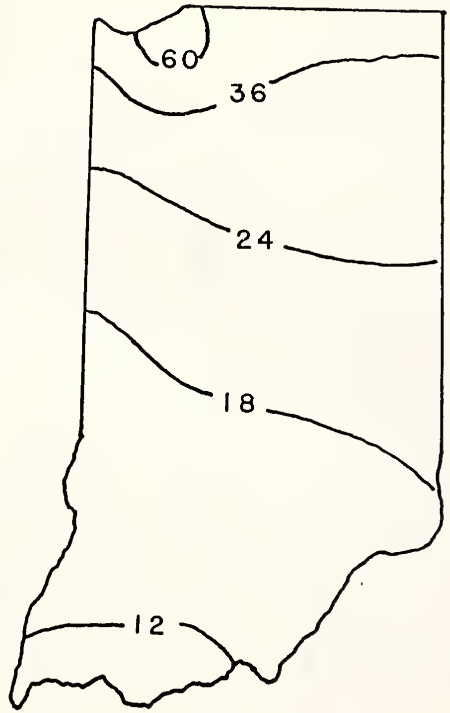


Figure 5.2 Distribution of Mean Annual Snowfall in Inches

University, a contour map for the mean annual snowfall in inches was prepared, as shown in Figure 5.2.

c. Mean Annual Rainfall -- The distribution of mean annual rainfall in inches for Indiana is shown in Figure 5.3.

d. Thornthwaite Moisture Index -- This index was developed by Thornthwaite [35] to classify climate on the basis of moisture and temperature. It has been used to relate to engineering properties and behavior of pavement materials in the area of moisture-related pavement distress analysis [36]. The distribution of Thornthwaite Moisture Index in Indiana is shown in Figure 5.4.

e. Freeze-Thaw Cycle Index -- Damage or deterioration of highway pavements, rigid pavements in particular, may be brought about by repeated cycles of freezing and thawing. Unfortunately, the number of freeze-thaw cycle in roadbed soil or in the pavement itself cannot be measured easily and such information is rarely available. In this study, an index based on fluctuations of air temperature was used to approximate the actual number of freeze-thaw cycles.

The procedure to compute the freeze-thaw cycle index was as follows. Daily maximum and minimum

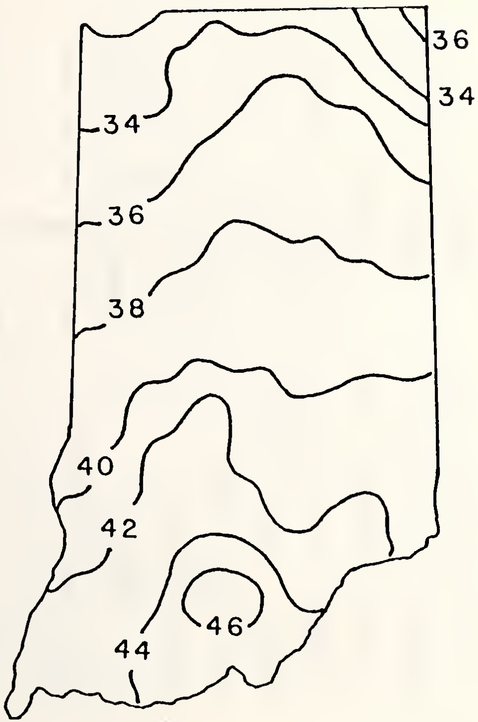


Figure 5.3 Distribution of Mean Annual Rainfall in Inches

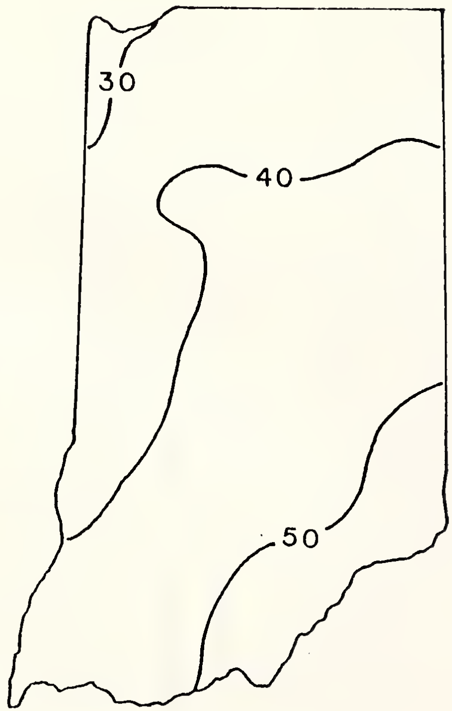


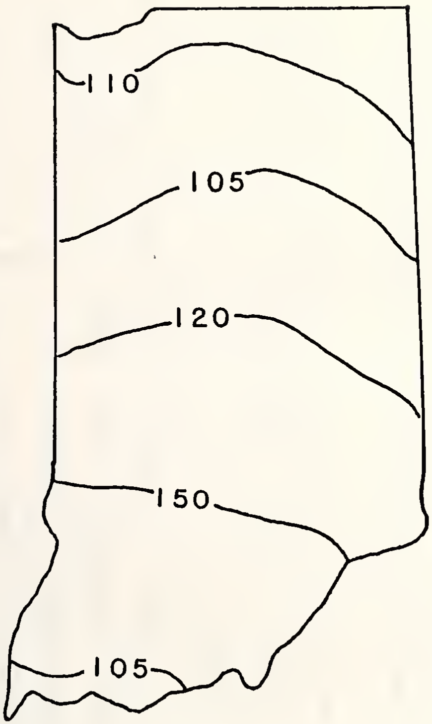
Figure 5.4 Distribution of Thornthwaite Moisture Index

temperatures at more than 90 locations in Indiana are available in the Indiana Climatological Data published monthly by the National Climatic Center [37]. Twelve stations and a period of 10 years (1974-1983) were considered in developing the freeze-thaw cycle index contour map in Figure 5.5(a). The locations of the twelve stations are given in Figure 5.5(b).

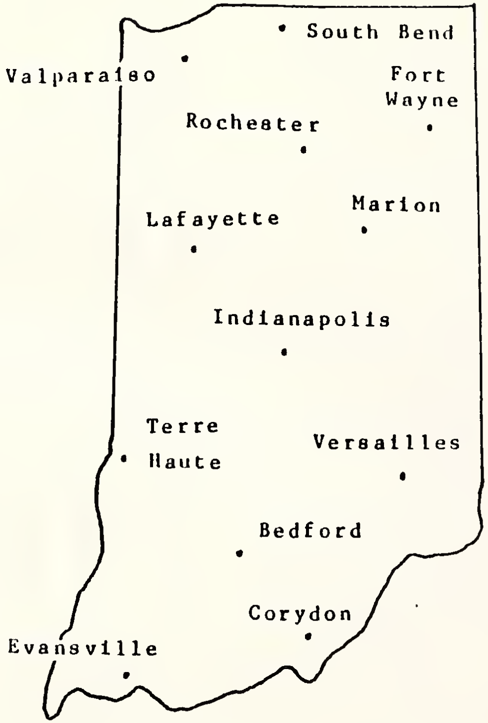
Each index value represents the mean annual number of air temperature change over the ten-year period. A temperature change is defined as a change of air temperature across the freezing temperature, 32^{o} F. It should be noted, however, that only six months (January through March, and October through December) in each year were included; and that the procedure had implicitly assumed a maximum of two temperature changes in a 24-hour period.

f. Annual Average Temperature -- The distribution of annual average temperature in Indiana is shown in Figure 5.6.

g. Soil Support Value -- The evaluation of soil support value for major soil types in Indiana has been described in Section 4.5.5. Figure 5.7 shows a simplified presentation of soils type distribution in Indiana. The soil support values used in the



(a) Contours of Freeze-Thaw Cycle Index



(b) Locations of Recording Stations

Figure 5.5 Distribution of Freeze-Thaw Cycle Index Values in Indiana

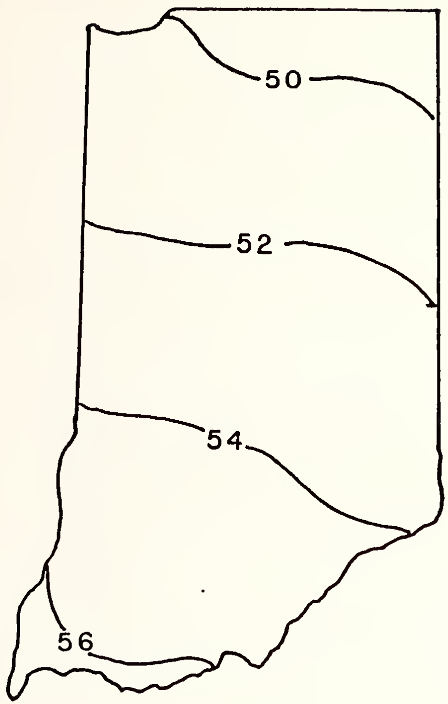


Figure 5.6 Distribution of Annual Mean Daily Temperature in Degree Fahrenheit

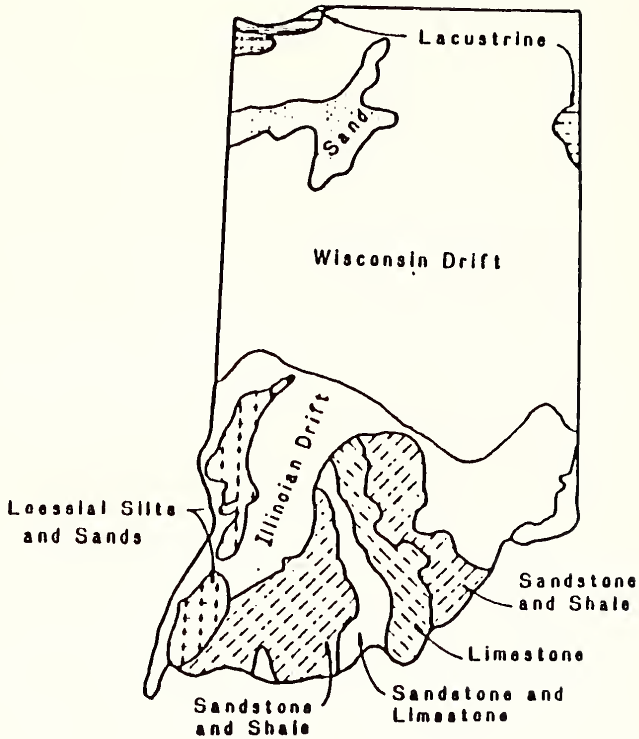


Figure 5.7 Distribution of Major Soil Types in Indiana

analysis were, however, evaluated using the original full-scale version of the map shown in Figure 4.2..

For each of the environmental indices discussed above, a common procedure was employed to compute a weighted value for a given highway route. Different sections (not necessarily highway sections) of a highway route were each assigned a value of a particular index in question, these values were then weighted by the length of their respective sections to arrive at a weighted index for the highway route.

5.4 Damage Responsibility and Pavement Type

The statistics of the damage responsibilities computed for rigid pavements and flexible pavements are summarized in Table 5.4. A detailed comparison of the performance analysis results of the two pavement types is difficult because of the following reasons: (i) different AASHTO performance equations for the two pavement types were used in the performance analysis; (ii) different PSI models were used to determine their field performance curves; (iii) pavement thickness of the two pavement types were not computed in the same manner; and (iv) vehicle ESALs for the two pavement types were calculated by different formulas.

Since, by definitions adopted in the present

Table 5.4 Pavement Damage Responsibilities of Indiana Highways by Pavement Types

Description	Rigid Pavement	Flexible Pavement
No. of Cases Analysed	6	69
Load-Related Responsibility %		
Range	52.4 to 67.7	71.3 to 100.0
Mean	62.52	90.60
Standard Deviation	5.87	6.23
Non-Load-Related Responsibility %		
Range	32.3 to 47.6	0.0 to 28.7
Mean	37.48	9.40
Standard Deviation	5.87	6.23

aggregate performance approach, the physical meaning of the term 'load-related responsibility' is directly related to ESAL and AASHTO performance equations, it would therefore be inappropriate to compare the magnitudes of damage responsibilities for the two pavement types presented in Table 5.4.

This same restriction also holds true for the disaggregate distress function methodologies discussed in Chapter 2 because the lack of a common basis for comparison would still exist. Distresses that are found in flexible pavements are different from those in rigid pavements. A flexible pavement distress classified as load-related cannot be compared to a rigid pavement distress which is also classified as load-related. There simply does not exist an absolute measure of load effects that permits a straight-forward comparison to be made. The use of distress weighting scheme in disaggregate distress function approach further complicates the matter.

Due to the limitation discussed above, pavement damage responsibility correlation analyses were carried out separately for the two pavement types.

5.5 Regional Effects on Damage Responsibility

5.5.1 Regional Zones in Indiana

Two environmental and climatic regions in Indiana have been commonly used in past studies [29,54,55,56]. These are the northern and the southern regions depicted in Figure 5.8.

It should be noted, however, that there is no stated criteria upon which one could define the dividing line between the two regions in Figure 5.8. The original basis of this grouping was the contours of equal regional factors shown in Figure 5.10 which was produced by Van Til et al. [18]. These contours were developed from an evaluation survey concerning the regional factors used in various states. It is important to recognize, as Van Til et al. pointed out in their report, that (i) no test results or physically measured quantities were used to derive these contours, and (ii) these regional factor values are meant to be related to flexible pavement performance.

Although the IDOH uses a uniform factor of 1.0 in their design of flexible pavement for the entire state of Indiana, Yoder et al.[52,53] found that the regional zones indicated in Figure 5.9 provide a reasonable assessment of the general climatic and environmental pattern for Indiana. It was suggested that the two regions as shown

Figure 5.8 Northern and Southern Regions in Indiana

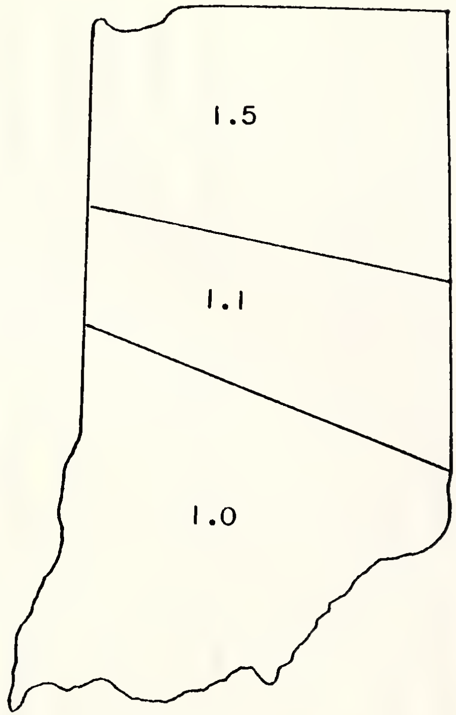


Figure 5.9 Regional Factor Zones for Indiana

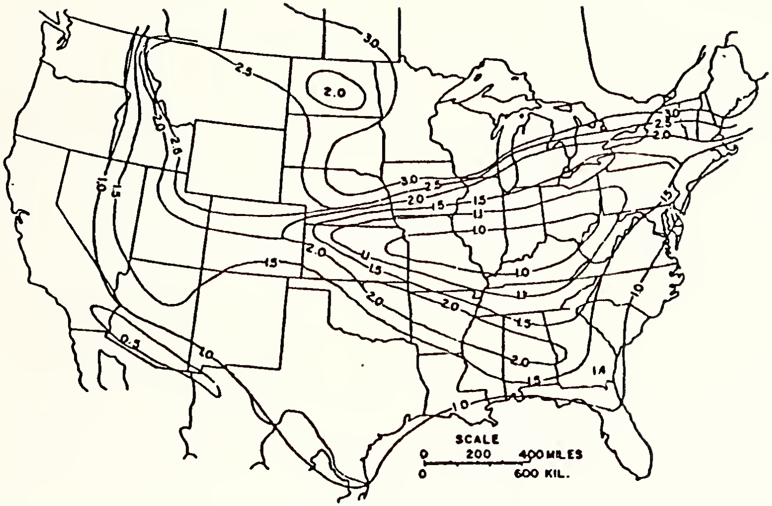


Figure 5.10 Generalized Regional Factors Map of the United States

in Figure 5.8, instead of the three regions in Figure 5.9, be used to represent the climatic and environmental conditions in Indiana for pavement evaluation purposes. This zoning criterion was later adopted by two subsequent studies concerned with pavement resurfacing programming [31] and pavement maintenance cost analysis [19].

The general characteristics of the two regions are illustrated in Table 5.5 which gives the ranges of values of various climatic and environmental variables. It is noted that while the northern region has a longer period with depressed temperature and heavier snowfall, the southern region receives more precipitation and experiences more changes of air temperature across the freezing point.

5.5.2 Statistical Analysis of Regional Effects

In investigating the effects the two regions have on the relative magnitudes of damage responsibilities of load-related and non-load-related factors, the following general regression model was adopted.

$$Y1_i = c_0 + c_1 Z + c_2 X2_i + c_3 X3_i + c_4 X4_i + c_5 X5_i + c_6 X25_i + e_i \qquad (5.1)$$

$i = 1, 2, \ldots, n$

Table 5.5 Characteristics of Northern and Southern Regions in Indiana

Climatic/Environmental Factors	Northern Region		Southern Region	
	Minimum	Maximum	Minimum	Maximum
Freezing Index (^{o}F-Day)	100	350	0	170
Mean Annual Snowfall (in.)	22	60	11	24
Mean Annual Rainfall (in.)	34	38	37	46
Mean Daily Temperature (^{o}F)	50	52	52	57
Thornthwaite Moisture Index	30	41	35	55
Freeze-Thaw Cycle Index	105	111	105	160
Soil Support Value	4.0	6.8	4.0	6.8

where

$Y1$ = percent damage responsibility of load-related effects

Z = 0 for southern region

1 for northern region

$X2$ = pavement age in years

$X3$ = slab thickness in inches for rigid pavement; structural number for flexible pavement

$X4$ = mean AADT

$X5$ = mean annual ESAL

$X25$ = total accumulated ESAL

e = random error term

c_k = regression parameters, $k=1, 2, \ldots, 6$

n = total number of observations

Only variables which are not characteristics of the two regions are included in the model. The environmental and climatic variables discussed in Section 5.3.3, which describe the conditions in each of the two regions, are qualitatively represented by the indicator variable Z.

Since the goal was to test if the percent damage responsibility of load-related effects was different in the two regions, no attempt was made to obtain the best regression model out of Equation (5.1). In drawing inferences about c_1, the relevant statistical test was:

$$H_0: \quad c_1 = 0$$

$$H_1: \quad c_1 \neq 0$$

5.5.3 Analysis for Flexible Pavements

The regression results for flexible pavement based upon the model in Equation (5.1) is summarized in Table 5.6. The conclusion is $c_1 \neq 0$ at both 0.05 and 0.01 level of significance. This means that the damage responsibilities on flexible pavements in the two regions were significantly different.

Due to its longer cold period and higher amount of snowfall, the northern region is commonly regarded as having a more severe climatic conditions than those at the southern region. The results in Table 5.6 indicate, with 99% confidence, that the load-related responsibility was less in the northern region. In other words, the non-load-related responsibility in the northern region was significantly higher than that in the southern region.

By representing each highway route by the location of its mid-point, a plot of damage responsibility percentages for flexible pavements is prepared in Figure 5.11 to show the general distribution pattern of these values. The vertical axis coordinate refers to the mid-point location of a highway route, measured northerly in miles from

Table 5.6 Statistical Analysis for Model in Equation (5.1) ---- Flexible Pavement

(a) Regression Analysis

Coeff.	Estimated Value	Standard Deviation	t Value
c_0	97.092	9.673	10.037
c_1	-8.435	1.019	-8.282(*)
c_2	-0.252	0.202	-1.246
c_3	-0.623	1.869	-0.333
c_4	-0.0001	0.0003	-0.330
c_5	21.318	13.39	1.592
c_6	-1.460	1.938	-0.753

(*) significant at lavels 0.05 and 0.01

(b) Analysis of Variance

Source of Variation	Sum of Squares	df	MS
Regression	1667.14	6	277.86
Error	967.79	62	15.61
Total	2634.93	68	

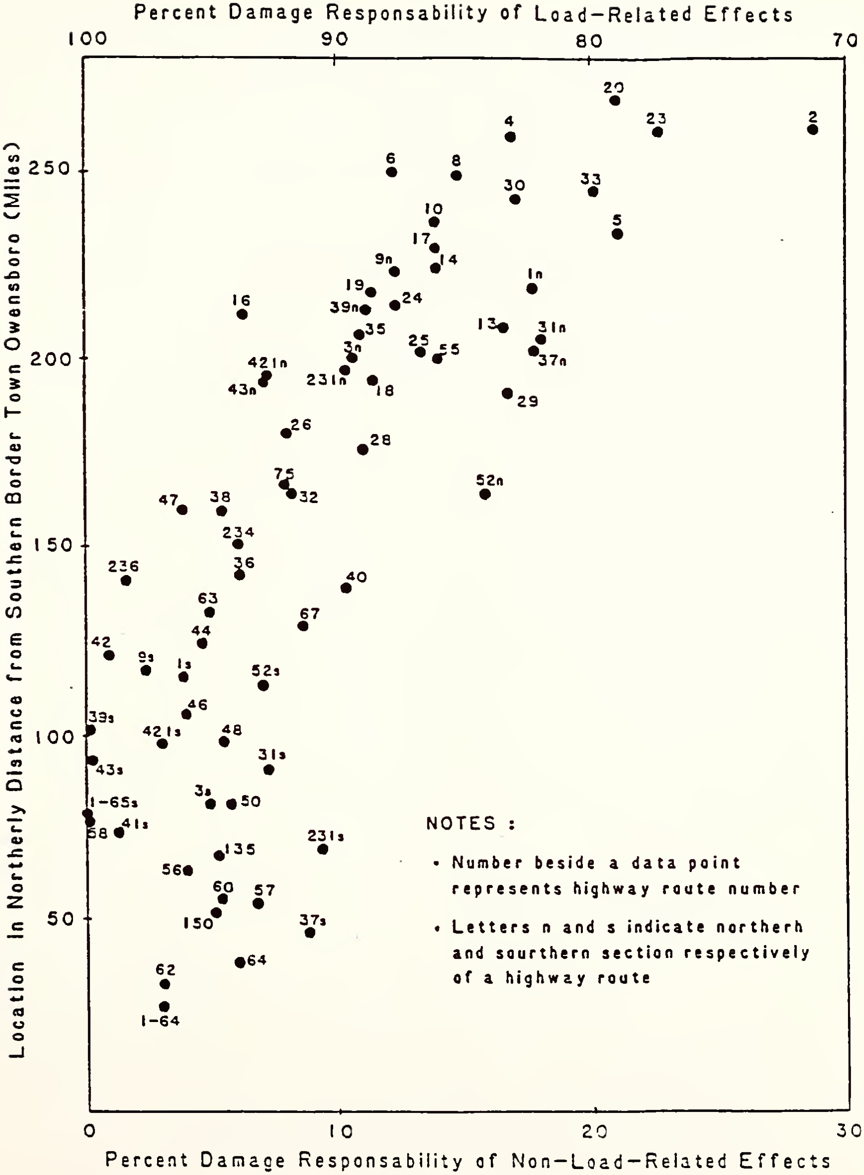


Figure 5.11 Regional Distribution of Damage Responsibility for Flexible Pavements in Indiana

Owensboro -- a small town located at the southern border of Indiana. A distinct distribution pattern of damage responsibilities can be observed from the plot. Non-load-related damage responsibility tends to become higher in the north as the weather becomes more and more severe.

5.5.4 Analysis for Rigid Pavements

Due to the small number of cases available for rigid pavements, a reduced version of the general model in Equation (5.1) was needed. Based upon the general goodness-of-fit measure represented by the coefficient of multiple determination (R^2), a reduced model with the highest value of R^2 was selected. The model employed was:

$$Y1_i = c_0 + c_1 Z_i + c_2 X2_i + e_i \qquad (5.2)$$
$$i = 1, 2, \ldots, 6$$

where all variables are defined in Equation (5.1).

The results of regression analysis and ANOVA are presented in Table 5.7. The regional effect is significant only at a level of significance equal to 0.248. It may therefore be concluded that, at 0.05 level of significance, there was no difference between the damage responsibilities in the two regions.

Table 5.7 Statistical Analysis for Model in Equation (5.2) ---- Rigid Pavement

(a) Regression Analysis

Coeff.	Estimated Value	Standard Deviation	t Value
c_0	90.6581	5.805	15.618
c_1	2.5675	1.7939	1.431(*)
c_2	-1.8171	0.3415	-5.321

(*) significant at lavel 0.248
not significant at level 0.05

(b) Analysis of Variance

Source of Variation	Sum of Squares	df	MS
Regression	157.85	2	78.925
Error	14.13	3	4.713
Total	171.98	5	

5.5.5 Relating Results to an Earlier Study

Sharaf [19,55] has made significant contributions in analyzing the highway routine maintenance costs in Indiana. A part of Sharaf's work dealt with the development of prediction models for routine maintenance costs. These models were expressed as functions of highway class, pavement type, traffic level and climatic zone.

Since identical climatic zones, and the same state highway system were analyzed over approximately the same period of time, it is interesting and informative to relate the results of Sharaf's work to those obtained in the present study. Sharaf concluded that, although all prediction models of different pavement types estimate higher values of maintenance expenditure in the northern region for a given level of traffic loading, there were insignificant differences statistically between the expenditures in the two regions.

This conclusion is important in that, together with the results in Section 5.5.3, it reveals an inconsistency between distribution of maintenance expenditures and the need for pavement repair on flexible pavements of the state highway system. While the conclusion in Section 5.5.3 indicates that climatic effects were playing a more significant role in the northern region, unit maintenance expenditure analysis results do not show a matching distribution of fund and activities.

5.6 Development of Damage Responsibility Prediction Models

One of the objectives of this study was to develop prediction models so that damage responsibilities of load-related and non-load-related effects may be estimated from easily available information such as pavement inventory data, traffic data, and data on environmental and climatic conditions.

5.6.1 Uses of a Damage Responsibility Prediction Model

A damage responsibility prediction model may find application in the following areas:

a. Highway Cost Allocation Analysis -- Although an aggregate performance approach methodology for pavement damage analysis does not require as much data, computing effort and time as required by a disaggregate distress function approach methodology, the amount of time and effort involved are still excessive if a periodic cost allocation analysis is to be carried out in every two or three years. The availability of a damage responsibility prediction model would greatly reduce the time and effort required in such a study, thereby permitting cost allocating analysis to be performed on a regular basis. Updating and improvement of prediction models may be carried out in the intervening period between two successive cost allocation studies.

b. Pavement Design -- While the predicted damage responsibilities obtained from a prediction model cannot be used directly in the present pavement design procedure, a high predicted environmental damage responsibility might indicate the need to provide, for instance, better drainage, the use of weather-resistant materials, or other precautionary measure.

c. Routine Maintenance Planning -- Information concerning relative damage responsibilities may aid routine maintenance planning at both project and network levels. At the project level, certain preventive maintenance work may be scheduled at critical periods of the year if the pavement concerned is predicted to have a high non-load-related responsibility. At network level, allocation of fund or human resources may be effected during the same critical periods so that areas which are likely to be affected more by climatic conditions would receive the deserved attention.

5.6.2 Flexible Pavement Damage Responsibility Models

All the variables, X2 through X12, and X25 that are listed in Table 5.3 were considered in the process of developing a prediction model for Y1, the percent responsibility of load-related effects. The correlation matrix for these variables are shown in Table 5.8.

An inspection of the correlation matrix reveals that there is a high coefficient of correlation between every pair of the six climatic variables, X6 through X11. The section of correlation matrix that contains this information is delineated by dotted lines in Table 5.8. This suggests that it is likely to be sufficient to have just one of these variables in a prediction model to represent climatic conditions.

Based solely upon the values of their respective coefficient of correlation with the dependent variable Y1, X6 (the freezing index) appears to be the best candidate for inclusion in a model. However, as can be expected from the high correlation among them, the differences are small. A more appropriate criterion might be the availability of these data. For example ,while rainfall or snowfall data were readily available at many locations, freezing index and Thornthwaite moisture index were not

Table 5.8 Correlation Matrix for Statistical Analysis of Damage Responsibilities on Flexible Pavements in Indiana

	Y1	X2	X3	X4	X5	X25	X6	X7	X8	X9	X10	X11	X12
Y1	--	.116	-.289	-.264	.162	.131	-.844	-.822	.761	.714	.718	.743	-.587
X2	.116	--	-.376	-.211	-.157	-.053	-.055	.009	-.078	-.117	-.085	-.095	-.289
X3	-.289	-.376	--	.654	.283	.249	.119	.124	-.105	-.118	-.055	-.100	-.024
X4	-.264	-.211	.654	--	.557	.553	.151	.112	-.053	-.041	-.077	-.039	-.022
X5	.162	-.157	.283	.557	--	.951	-.131	-.177	.222	.228	.143	.229	-.112
X25	.131	-.053	.249	.553	.951	--	-.113	-.170	.223	.229	.070	.232	-.124
X6	-.844	-.055	.119	.151	-.131	-.113	--	.971	-.905	-.835	-.821	-.884	.737
X7	-.822	.009	.124	.111	-.177	-.170	.971	--	-.975	-.937	-.868	-.962	.699
X8	.761	-.078	-.105	-.053	.222	.223	-.905	-.975	--	.984	.870	.999	-.624
X9	.715	-.117	-.119	-.041	.228	.228	-.835	-.937	.984	--	.880	.989	-.564
X10	.718	-.085	-.055	-.077	.143	.070	-.821	-.868	.870	.880	--	.868	-.556
X11	.743	-.095	-.100	-.039	.229	.232	-.884	-.962	.999	.989	.868	--	-.602
X12	-.587	-.287	-.023	-.022	-.112	-.124	.737	.700	-.625	-.564	-.556	-.602	--

so. There are therefore good practical reasons to present a few alternative models in addition to the so-called 'best' regression model [40,41].

The SPSS stepwise regression search method [49] was used to arrive at a 'best' set of independent variables. The model obtained with this method is given in Equation (5.3).

$$Y1 = 112.378 - 0.03217(X6) - 3.25105(X3) \qquad (5.3)$$

where

Y1 = percent responsibility of load-related effects

X6 = freezing index in degree-days

X3 = pavement thickness in structural number

Similar prediction models in terms of other climatic variables are given in Equations (5.4) through (5.8) below.

$$Y1 = 123.495 - 0.60257(X7) - 3.22925(X3) \qquad (5.4)$$

$$Y1 = 25.611 + 2.11301(X8) - 3.60559(X3) \qquad (5.5)$$

$$Y1 = 64.465 + 1.00411(X9) - 3.52824(X3) \qquad (5.6)$$

$$Y1 = 78.871 + 0.26264(X10) - 4.26178(X3) \qquad (5.7)$$

$$Y1 = -42.356 + 2.86816(X11) - 3.69222(X3) \qquad (5.8)$$

where

X7 = Mean annual snowfall in inches

X8 = Mean annual rainfall in inches

X9 = Thornthwaite moisture index

X10 = Freeze-thaw cycle index

X11 = Annual average temperature

Regression analyses were also carried out to study the effects of having interaction terms in the above models. The terms considered are interaction between climatic and pavement characteristic variables, interaction between climatic and traffic loading variables, and interaction between climatic variables and soil support value. No significant improvement in R^2 value was found for any of the models with the inclusion of interaction terms.

A summary of the regression characteristics of the models presented in Equations (5.3) through (5.8) is given in Table 5.9. As seen from this table, models (5.3) and (5.4) in which freezing index and snowfall data are used respectively, have higher R^2 value than the rest. Since snowfall information is more readily obtainable from commonly available climatological data than freezing index, model (5.4) appears to be the most practical model.

The R^2 values for reduced models containing only a climatic variable were also computed and shown in Table 5.9. These results indicate that more than half of the variation in Y1 could be explained by any one of the six climatic variables. This implies that climatic variables

Table 5.9 Statistical Characteristics of Damage Responsibility Models for Flexible Pavements

Description	Model (5.3)	Model (5.4)	Model (5.5)	Model (5.6)	Model (5.7)	Model (5.8)
Climatic Variable	X6	X7	X8	X9	X10	X11
Pavement Variable	X3	X3	X3	X3	X3	X3
No. of Data Points	69	69	69	69	69	69
Coefficient of Determination R^2	0.7482 (0.7125)*	0.7114 (0.6762)*	0.6233 (0.5792)*	0.5532 (0.5111)*	0.5773 (0.5151)*	0.5984 (0.5521)*
Linearity Test						
F value	166.04	81.36	54.60	40.87	45.06	45.18
α level	0.000	0.000	0.000	0.000	0.000	0.000
Test for Coefficient						
Climatic Variable						
F value	174.33	143.68	94.63	69.43	77.13	84.68
α level	0.000	0.000	0.000	0.000	0.000	0.000
Pavement Variable						
F value	9.37	8.06	7.73	6.22	9.69	7.61
α level	0.003	0.006	0.007	0.015	0.003	0.008

* Value in parenthesis refers to R^2 for the reduced model
$Y1 = b_0 + b_1$(Climatic Variable)

were the most important factors in predicting the damage responsibilities on flexible pavements in Indiana.

It is important to note that the models developed are statistical in nature, they are not mechanistic models. Caution must be exercised in interpreting the meaning of a regression model. The presence of a regression relation between an independent variable and a set of dependent variables, such as a high R^2 value, does not prove the existence of a cause-effect relationship between them.

This point can be illustrated by considering the regression relationship between damage responsibility and mean annual rainfall expressed in Equation (5.5). This model suggests that as annual rainfall decreases, climatic effects (approximated by 1-Y1) increases. This is contradictory to the common engineering understanding that increased moisture content in subgrade soil due to rainfall has an adverse effect on pavements [58,59,60].

The explanation to this seemingly paradoxical relationship lies in the fact that rainfall was only one of a number of climatic factors that influenced pavement performance. Although rainfall was higher in the southern region, other climatic factors were less severe in this region. The computed damage responsibilities were the results of combined action of traffic loadings and all climatic and environmental factors. An erroneous conclusion would be obtained if one derives a cause-effect relationship based upon only a single regression model.

5.6.3 Rigid Pavement Damage Responsibility Models

In general, high correlation coefficient values were also found for each climatic variable pair of rigid pavement data. The correlation matrix in Table 5.10 indicates that, with the exception of freeze-thaw cycle, there are low correlations between climatic conditions and damage responsibility. This finding concurs in general with an earlier conclusion in Section 5.5.4 that the regional effects on damage responsibility of rigid pavement are insignificant.

All the six rigid pavement highways considered have the same slab thickness of 10 inches. The model developed in this study is therefore valid for one slab thickness only. The other pavement characteristic variable, the pavement age X2, has a high coefficient of correlation with damage responsibility.

At a 0.05 level of significance, all variables other than X2 were found to be insignificant in explaining the variation of damage responsibility Y1. This led to the following prediction model:

$$Y1 = 93.157 - 1.8922(X2) \tag{5.9}$$

Table 5.10 Correlation Matrix for Statistical Analysis of Damage Responsibilities on Rigid Pavements in Indiana

	Y1	X2	X4	X5	X25	X6	X7	X8	X9	X10	X11	X12
Y1	--	-.928	.532	.543	.404	.393	.235	.036	.047	-.679	.009	.497
X2	-.928	--	-.347	-.368	-.191	-.143	.009	-.279	-.236	.559	-.206	-.323
X4	.532	-.347	--	.994	.976	.896	.821	-.730	-.568	-.407	-.689	.920
X5	.543	-.368	.994	--	.980	.867	.814	-.729	-.595	-.366	-.704	.873
X25	.404	-.191	.976	.980	--	.874	.846	-.813	-.627	-.256	-.765	.841
X6	.393	-.143	.896	.867	.874	--	.956	-.854	-.726	-.604	-.813	.913
X7	.235	.009	.821	.814	.846	.956	--	-.950	-.897	-.480	-.944	.769
X8	.036	-.279	-.730	-.729	-.813	-.854	-.950	--	.932	.196	.975	-.635
X9	.047	-.236	-.568	-.595	-.657	-.726	-.897	.932	--	.212	.982	-.426
X10	-.679	.559	-.407	-.336	-.256	-.604	-.480	.196	.212	--	.226	-.590
X11	.009	-.207	-.689	-.705	-.765	-.813	-.944	.975	.982	.226	--	-.568
X12	.497	-.323	.920	.873	.841	.913	.769	-.635	-.426	-.590	-.568	--

The results of regression analysis are presented in Table 5.11 and Figure 5.12. Pavement age alone could explain 86.17% of the variation in the damage responsibility Y1.

Since the model in Equation (5.9) is statistical in nature, one should be aware of the inference space upon which it was derived. In particular, it should be emphasized that only one slab thickness of 10 inches was considered; and that since all the cases analyzed were Interstate highways, the traffic levels on these routes did not vary over a very wide range.

5.7 Summary Remarks

The results of the analyses performed in this chapter are summarized and major findings are highlighted in this section. Also included is a discussion concerning how these results should and should not be interpreted.

Two basic pavement types were considered in the analysis. Due to the fact that only gross performance information in terms of serviceability is required in an aggregate performance approach analysis, further breakdown of the pavement types into more detailed classes was found unnecessary. Since the performance equations and serviceability evaluation models used to describe the pavement types were different, there did not exist a

Table 5.11 Statistical Characteristics of Damage Responsibility Models for Rigid Pavements

Description	Model (5.9)
No. of Data Points	6
Coefficient of Determination R^2	0.8617
Adjusted Coefficient adj. R^2	0.8217
Linearity Test	
F value	24.913
α level	0.008
Test for X2 Coefficient	
F value	24.913
α level	0.008

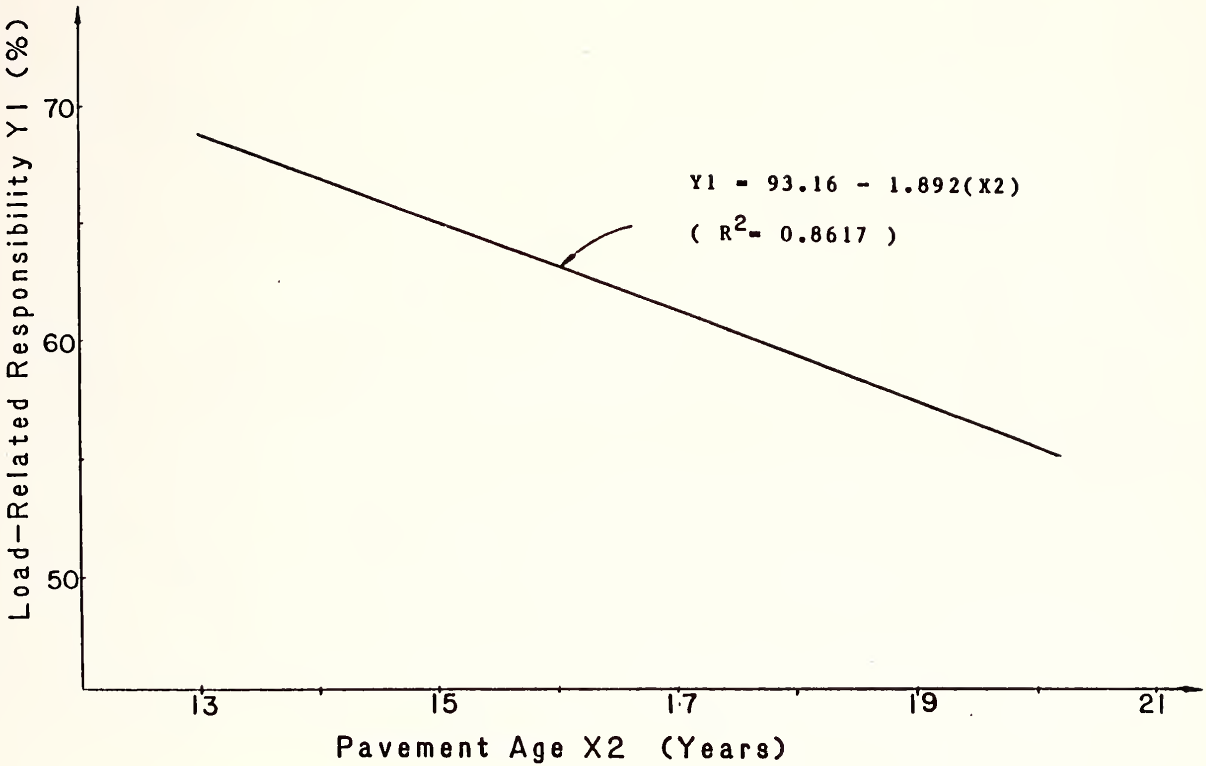


Figure 5.12 Load-Related Damage Responsibility on Rigid Pavements

common basis to combine or compare their damage responsibility results. Consequently, separate analyses were conducted and different damage responsibility models were developed for the two pavement types.

An analysis was first conducted to investigate regional effects on the magnitude of pavement damage responsibility. Based upon the findings of past studies, a northern and a southern region were used to represent the climatic and environmental conditions in Indiana. The damage responsibilities on flexible pavements were found to be significantly different in the two regions. There were, however, no significant differences in the case of rigid pavements.

Relating the results of regional effect analysis to the results of an earlier study dealing with routine maintenance cost analysis revealed an imbalance in the distribution of pavement routine maintenance fund and effort between the northern and the southern regions.

Prediction models were developed for estimating damage responsibilities on both flexible and rigid pavements. While climatic variables were able to explain reasonably well the variations in damage responsibility on flexible pavements, they could not explain much of the variations in damage responsibility on rigid pavements.

It is appropriate to mention here that the number of rigid pavement cases was rather small, despite the fact that more than 80% of the total rigid pavement mileage was represented in the study. Unfortunately, this problem of too few data points could not be solved as there simply did not exist many rigid pavement highways in Indiana.

CHAPTER 6

RELATIONSHIP BETWEEN ROUTINE MAINTENANCE AND PAVEMENT PERFORMANCE

6.1 Introduction

In the aggregate performance approach for pavement deterioration analysis, presented in Chapter 3, the following general assumptions were made regarding the relationship between pavement routine maintenance and pavement performance:

a. Pavement performance was assumed to be positively related to routine maintenance levels. This means that, for a given pavement section, the higher the level of routine maintenance, the higher would be the level of pavement performance.

b. A mathematical relationship, be it mechanical or statistical, was assumed to exist between pavement performance and level of pavement routine maintenance.

The application of the aggregate performance approach methodology to the 1983-84 Indiana Highway Cost Allocation Study provided a case study which could be used to examine the validity or reasonableness of the above assumptions.

6.2 Quantitative Representation of Level of Pavement Routine Maintenance

The selected quantitative measure for the level of routine maintenance on a given highway section was the maintenance expenditure per lane-mile of the highway section. This same measure was also used by Sharaf [19] in studying relationships between pavement maintenance expenditures and independent variables such as climatic conditions and traffic loadings.

It is known that different maintenance activities would not have the same unit costs [19,68]. Since the type and extent of distresses are likely to be different on highways with different pavement characteristics (age, thickness and materials), subsoil and climatic environment and traffic loadings, it is clear that maintenance cost per lane-mile cannot be used as a parameter to compare the levels of routine maintenance on two different pavements. However, for a highway route having homogeneous pavement characteristics and similar traffic loadings as well as environmental and climatic conditions over its entire length, the unit cost parameter can offer a meaningful comparison of the levels of maintenance performed on different highway sections of this route.

It is noted that the very concept of the proposed aggregate performance approach required that all the highway sections in an analysis be of the same design and with uniform pavement characteristics. Furthermore, these highway sections included were generally subjected to similar climatic, environmental and traffic conditions. It may therefore be concluded that the parameter of maintenance cost per lane-mile was a valid representation of level of pavement routine maintenance for the analyses performed in this research study.

6.3 Quantitative Representation of Pavement Performance

It has long been recognized that pavement performance is a manifestation of the aggregate response of a pavement in question under the combined effects of traffic loads, environment, age, initial design and construction, routine maintenance policy and amount of past maintenance [69,70,71]. A performance curve therefore is a result of the interaction between pavement characteristics and externally imposed effects.

It follows that any quantitative measure derived from a performance curve refers to the state of conditions of a given pavement with a known set of pavement characteristics. The quantitative representation of performance curve, PSI-ESAL loss, must also be interpreted as such.

It is of importance to keep in mind that a comparison of PSI-ESAL losses is meaningful in the performance analysis of a highway route only if the pavement sections under consideration possess homogeneous pavement characteristics. This may be explained by considering the example in Figure 6.1.

Shown in Figure 6.1 are performance curves of two pavements with different pavement characteristics. Both pavements are maintained by a given highway agency and the same level of routine maintenance is applied to both. Since pavement characteristics are not the same, different performance curves are obtained for the two pavements. At an arbitrary stage ′a′ the two pavements would have different PSI-ESAL losses as given by areas D and E in Figure 6.1, despite having the same per lane-mile maintenance cost spent on both pavements. This shows that, for a given level of maintenance specified by maintenance cost per lane-mile, the measure PSI-ESAL loss cannot be used to differentiate between pavement performance curves of pavements with different pavement characteristics. In other words, PSI-ESAL loss is a unique representation of pavement performance for

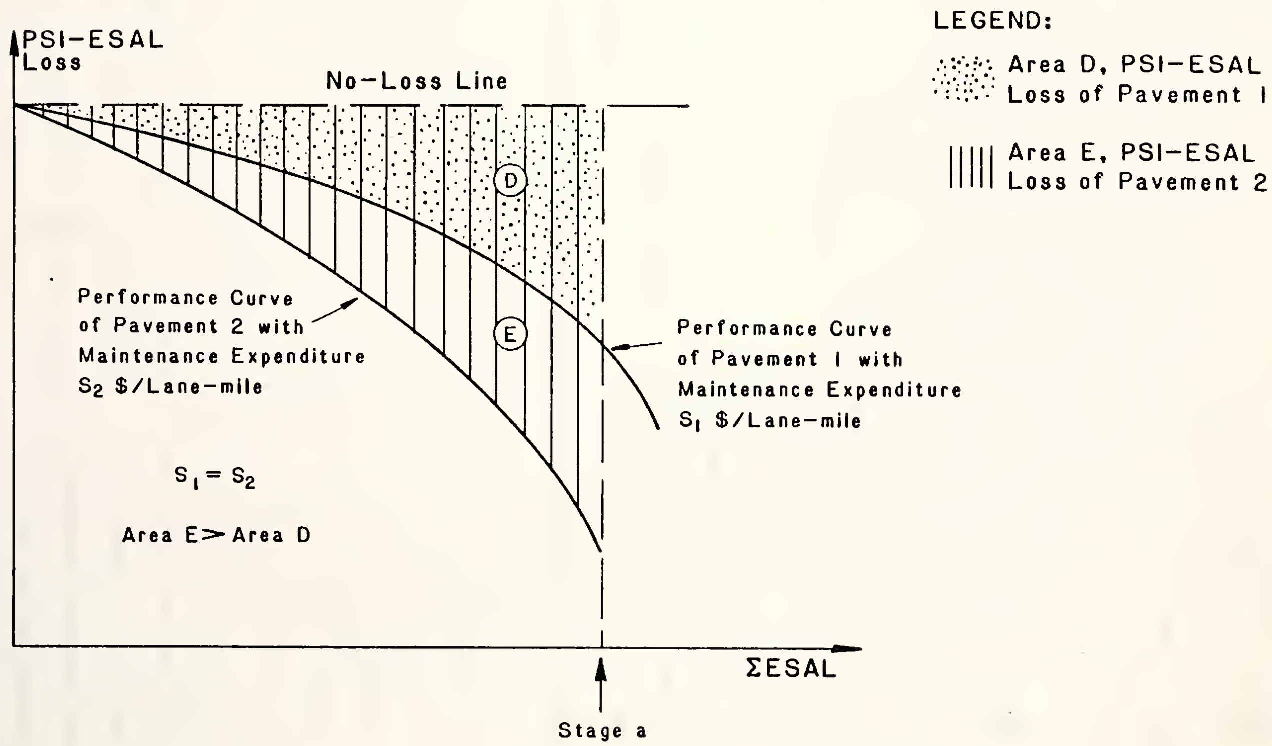


Figure 6.1 Performance Curves of Pavement Sections with Different Pavement Characteristics

different pavement sections only if the pavement characteristics of these pavement sections are the same.

It is also possible that different maintenance policy and maintenance technology may give rise to different pavement performance even though the amount spent per lane-mile and the pavement characteristics on different pavements are the same. This situation is depicted in Figure 6.2. It represents another example in which different PSI-ESAL losses are found with pavements maintained by the same expenditure per lane-mile.

The examples in Figure 6.1 and 6.2 indicate that a performance analysis based upon relationships between level of pavement routine analysis and pavement performance, expressed in terms of maintenance expenditure per lane-mile and PSI-ESAL loss respectively, would be valid if the following two requirements are met:

1. The highway sections included in each independent performance analysis must be homogeneous in pavement characteristics.

2. The maintenance policy and technology must be uniform over the entire length of the highway route analyzed.

The first requirement has been shown to be satisfied in the discussion in Section 6.2. As for the second requirement, a review of the routine maintenance practice

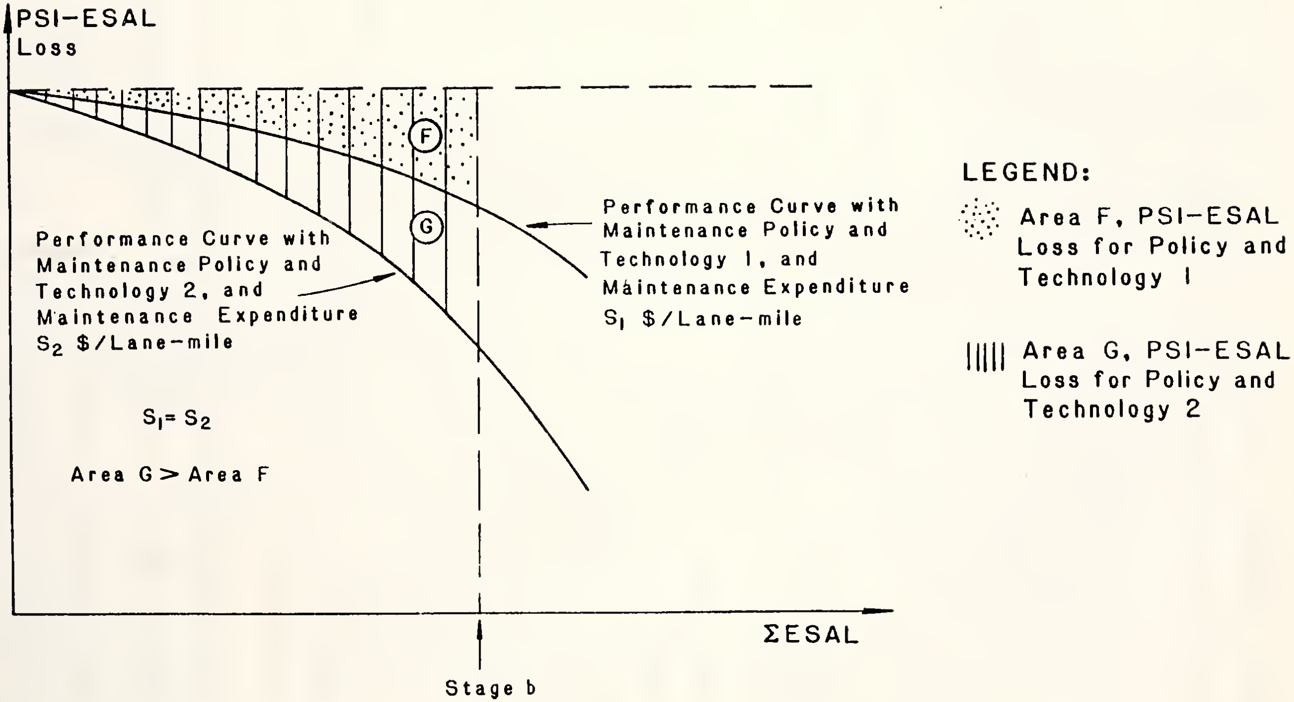


Figure 6.2 Performance Curves of Pavement Sections Maintained with Different Maintenance Policies and Technologies

in Indiana is needed to assess if it is fulfilled.

A recent study by Sanderson and Sinha [72] provides an insight into the management and programming of routine maintenance in Indiana. There are three levels of management in the IDOH Division of Maintenance: central office level, district level and the subdistrict level. Before the beginning of each fiscal year, personnel from the central office visit different subdistricts to determine maintenance needs. Adjustments to the maintenance program are subsequently made by the managers from all three levels before the program is finalized. Due to such close liaison among the three levels, it appears logical to conclude that there is a reasonably uniform maintenance policy and technology across the state of Indiana. That is, the second requirement may be considered to be satisfied for the performance analysis on Indiana highways presented in this dissertation.

There is a significant implication about fulfilling the two stated requirements. It means that a performance curve can thereby be uniquely defined by the parameter PSI-ESAL loss for a given level of pavement routine maintenance designated in terms of dollar amount of maintenance expenditure per lane-mile. To put it mathematically, there is a one-to-one correspondence between the two quantities, PSI-ESAL loss and dollar maintenance expenditure per lane-mile, under the conditions stated in requirements 1 and 2 mentioned above.

6.4 Positive Correlation of Level of Maintenance and Pavement Performance

The discussion in Section 6.2 and 6.3 has established that PSI-ESAL loss and the dollar maintenance expenditure per lane-mile are respectively valid representation of pavement performance and level of pavement routine maintenance in the context of the performance analysis concept followed in this dissertation; and that the relationship between level of pavement routine maintenance and pavement performance can be examined by considering the relationship between these two quantitative measures.

This section examines the validity of assumption (a) stated in Section 6.1. This assumption says that for each highway route which satisfies the two requirements in Section 6.3, the levels of pavement routine maintenance are positively related to pavement performance.

The detailed results of correlation analysis between PSI-ESAL losses and dollar maintenance expenditures per lane-mile for 69 cases of flexible pavement routes and 6 cases of rigid pavement routes are given in Tables A.1 and A.2 in the Appendix. The signs of coefficients of correlation, R, are of special interest because the main concern now is to check if levels of maintenance are indeed correlated positively to pavement performance.

The distribution of the values of R is shown in the form of a histogram in Figure 6.3 for 68 cases, including 62 flexible pavement and 6 rigid pavement cases. Seven flexible pavement cases which have two data points and a R value of -1.00 each are not included in the histogram presented in Figure 6.3. The results clearly show that, in all the 75 cases analyzed, high PSI-ESAL losses were associated with low maintenance expenditures. In other words, low pavement performance was associated with low level of pavement maintenance, and vice versa. These results therefore provide ample evidence that the assumption of positive correlation between pavement performance and levels of pavement routine maintenance was valid for the performance analysis on Indiana highways.

6.5 Suitability of Linearity Assumption

There is no known published relationships between level of pavement routine maintenance and pavement performance. The state-of-the-art knowledge in pavement performance evaluation technology has not advanced to a stage where a comprehensive technical analysis can be carried out to derive such a relationship. As an approximation to the true relationship between level of maintenance and pavement performance, a regression technique was adopted in this study to fit a least square

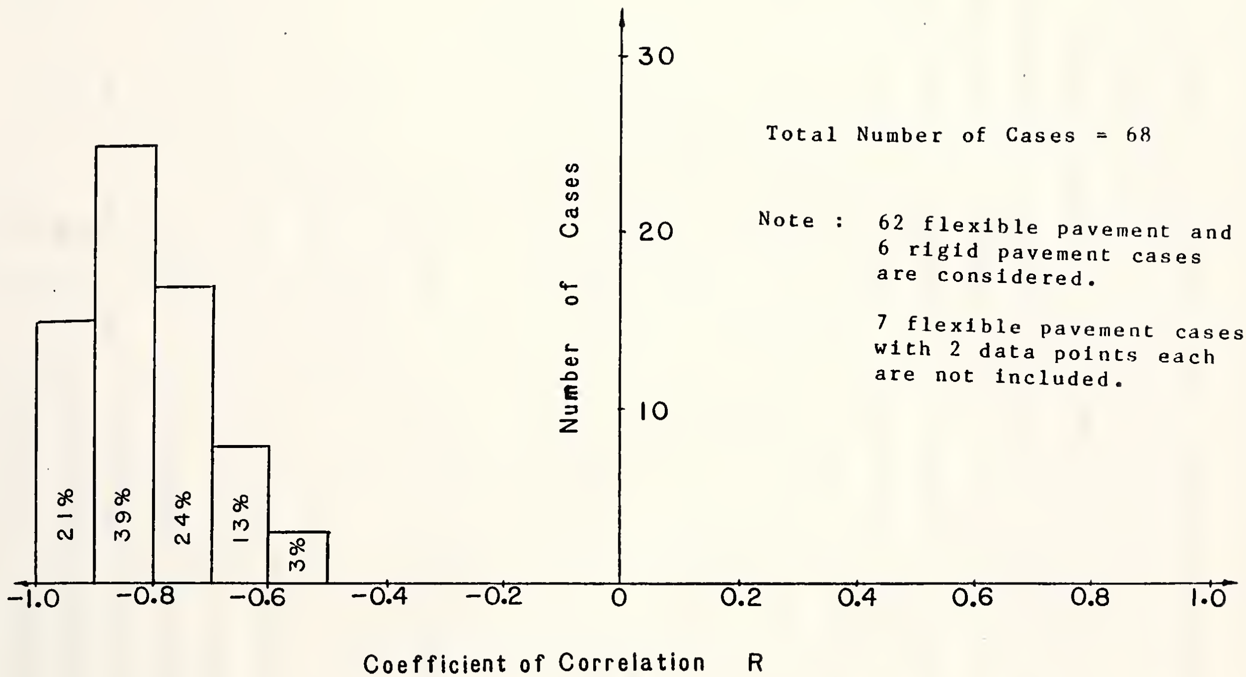


Figure 6.3 Distribution of R Values Correlating PSI-ESAL Losses and Dollars Maintenance Expenditure Per Lane-Mile of Pavement

line to the data points in the performance analysis of each highway route.

The suitability of the linearity assumption were checked by the following two criteria: (i) The general goodness-of-fit represented by the coefficient of multiple determination, R^2, was examined. It provides a measure of the degree of association or correlation that exists between the two variables. (ii) A t-test on the population correlation coefficient, ρ, was performed to determine whether or not the linear relationship offered an adequate explanation of the true situation.

The value of R^2 for each of the 69 flexible pavement routes and 6 rigid pavement routes are found in Tables A.1 and A.2 in the Appendix. A histogram of these values is presented in Figure 6.4. It can be seen that although there is a relatively wide range of R^2 values, the majority (about 75%) of the cases analyzed have R^2 higher than 0.60.

Due to the relatively small number of data points available for each highway route, an adjusted coefficient of multiple determination [40] was computed for each route to give an indication of the effect this limitation might have. The adjusted R^2 values for all the cases analyzed were calculated in Tables A.1 and A.2 and are presented in a histogram form in Figure 6.5. The percentage of cases

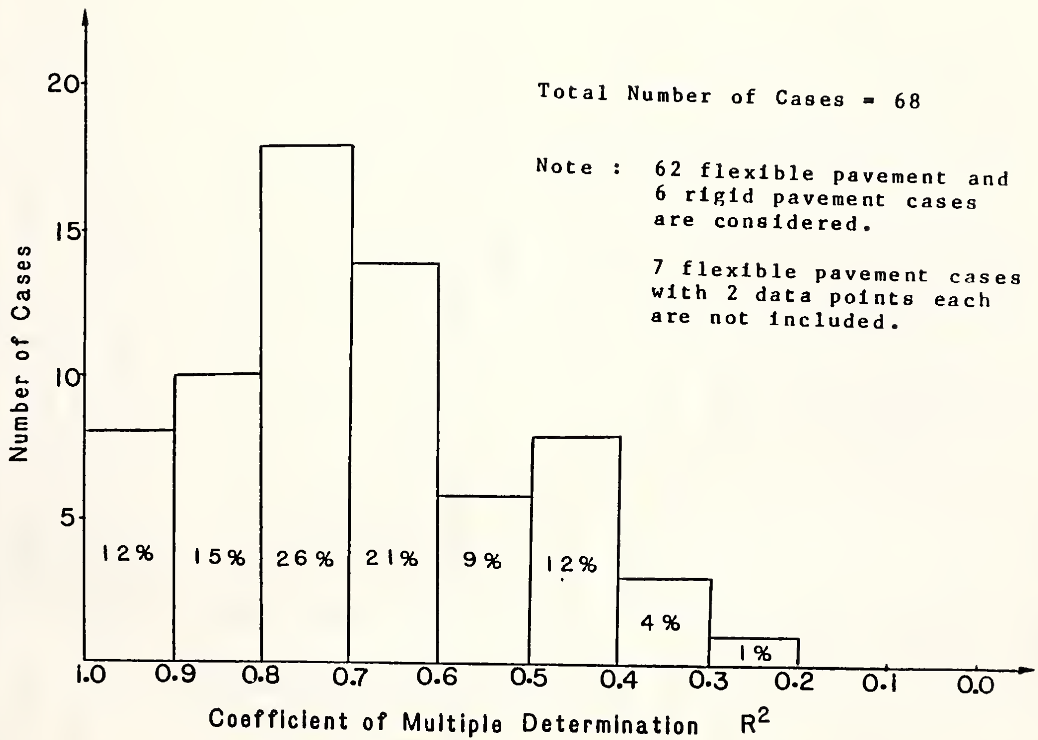


Figure 6.4 Distribution of R^2 Values Correlating PSI-ESAL Losses and Dollars Maintenance Expenditure Per Lane-Mile of Pavement

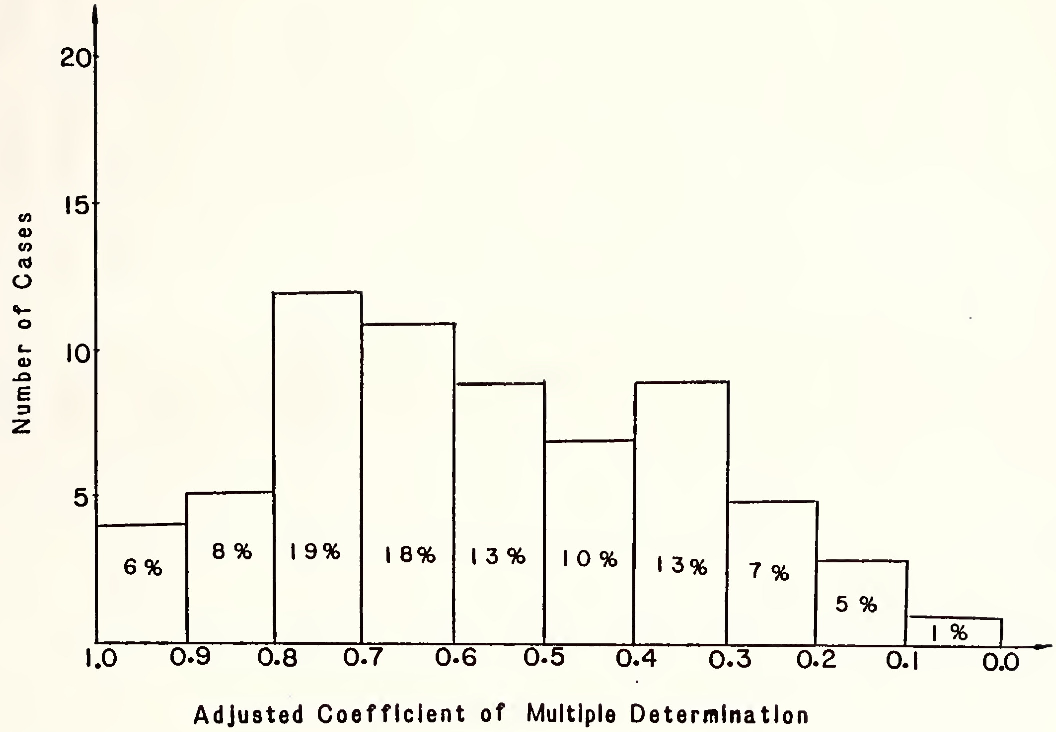


Figure 6.5 Distribution of Adjusted R^2 Values Correlating PSI-ESAL Losses and Dollars Maintenance Expenditure Per Lane-Miles of Pavement

with R^2 higher than 0.60 now becomes 51%.

The t-test for significance of linear relationship involves testing the null hypothesis that $\rho = 0$ versus the alternative $\rho \neq 0$. Symbolically, it is

$$H_0: \quad \rho = 0$$

$$H_1: \quad \rho \neq 0$$

The results of this test are found in Tables A.1 and A.2 in the Appendix. A breakdown of these results is presented in Table 6.1. Table 6.1(a) indicates that linear relationship was significant for about one-third of the cases at 5% level of significance, and for slightly more than half of the cases at 10% level of significance. If only those cases with five or more data points were considered, there were 41 eligible cases. Table 6.1(b) shows a much improved result where the test was significant for 61% and 80% of the cases respectively at 5% and 10% level of significance.

Another way to asses the quality of the results of these correlation analyses is to look at the width of interval estimate of the population correlation coefficient, ρ, for each of the performance analyses performed [78]. The computed 95 percent confidence intervals of ρ for the flexible and rigid pavement cases analyzed are presented in Tables 6.2 and 6.3 respectively.

Table 6.1 Significance Test for Linear Relationship between PSI-ESAL Loss and Mean Annual Maintenance Expenditure Per Lane-Mile

(a) Results for Cases with 3 or more Data Points

Level of Significance	Percent of Cases for which Linear Relationship is Significant
0.05	36.8 %
0.10	53.2 %
0.15	69.4 %
0.20	82.3 %

Note : Total number of cases = 68
Not including 7 flexible pavement cases with 2 data points each

(b) Results for Cases with 5 or more Data Points

Level of Significance	Percent of Cases for which Linear Relationship is Significant
0.05	61.0 %
0.10	80.5 %
0.15	95.1 %
0.20	100.0 %

Note : Total number of cases = 41

Table 6.2 95 Percent Confidence Intervals for Population Correlation Coefficients of Flexible Pavement Cases

Highway Route	Coefficient of Correlation R	Confidence Interval Lower Limit	Upper Limit
SR 1(n)	-0.7847	-0.996	0.717
SR 1(s)	-0.7989	-0.986	0.282
SR 2	-0.8238	-0.997	0.659
SR 3(n)	-0.8749	-0.986	-0.219
SR 3(s)	-0.8931	-0.993	-0.051
SR 4	-0.8981	-----	-----(*)
SR 5	-0.9600	-----	-----(*)
US 6	-0.8417	-0.976	-0.243
SR 8	-0.9751	-----	-----(*)
SR 9(n)	-0.6507	-0.957	-0.340
SR 9(s)	-0.8721	-----	-----(*)
SR 10	-0.8888	-0.997	0.495
SR 13	-0.8136	-0.979	-0.007
SR 14	-0.8905	-0.993	-0.041
SR 16	-0.8474	-0.977	-0.259
SR 17	-1.0000	-----	-----(*)
SR 18	-0.8772	-0.998	0.535
SR 19	-0.7074	-0.979	0.556
US 20	-0.9108	-0.994	-0.146
SR 23	-1.0000	-----	-----(*)
US 24	-0.9586	-0.998	-0.614
SR 25	-0.7798	-0.995	0.723
SR 26	-0.9074	-0.986	-0.486
SR 28	-0.7525	-0.961	-0.000
SR 29	-1.0000	-----	-----(*)
US 30	-0.9370	-0.991	-0.625
US 31(n)	-0.8788	-0.978	-0.458
US 31(s)	-0.9863	-0.999	-0.797
SR 32	-0.7638	-0.963	-0.025
SR 33	-0.7000	-0.979	-0.476
US 35	-0.6728	-0.946	0.162
US 36	-0.7951	-0.976	0.047
SR 37(n)	-0.9601	-----	-----(*)
SR 37(s)	-0.9828	-----	-----(*)
SR 38	-0.8397	-0.989	0.163

Table 6.2 (continued)

Highway Route	Coefficient of Correlation R	Confidence Interval Lower Limit	Confidence Interval Upper Limit
SR 39(n)	-0.8812	-0.997	0.163
SR 39(s)	-0.8438	-0.996	0.522
US 40	-0.7380	-0.994	0.767
US 41	-0.5956	-0.916	0.645
SR 42	-0.7934	-----	-----(*)
SR 43(n)	-1.0000	-----	-----(*)
SR 43(s)	-1.0000	-----	-----(*)
SR 44	-0.8847	-0.988	-0.261
SR 46	-0.6463	-0.929	0.108
SR 47	-0.6456	-----	-----(*)
SR 48	-0.9925	-----	-----(*)
US 50	-0.6930	-0.963	0.265
US 52(n)	-0.7346	-0.948	0.063
US 52(s)	-1.0000	-----	-----(*)
SR 55	-0.8835	-0.992	-0.008
SR 56	-0.6645	-0.945	0.178
SR 57	-0.5783	-0.967	0.621
SR 58	-0.8605	-----	-----(*)
SR 60	-0.6441	-0.936	-0.169
SR 62	-0.8035	-----	-----(*)
SR 63	-0.9160	-----	-----(*)
SR 64	-0.8735	-0.986	-0.213
I 64	-0.6128	-0.991	0.847
I 65(s)	-0.9131	-0.998	0.392
SR 67	-0.8113	-0.971	-0.761
SR 75	-0.9475	-0.999	0.147
SR 135	-0.8989	-0.985	-0.452
US 150	-1.0000	-----	-----(*)
US 231(n)	-0.7488	-0.960	0.009
US 231(s)	-0.8611	-0.984	-0.164
SR 234	-0.8395	-0.982	-0.089
SR 236	-0.8726	-0.997	0.547
US 421(n)	-0.7923	-0.976	0.055
US 421(s)	-0.8231	-----	-----(*)

(*) Confidence intervals are not given for cases with 3 or less data points

Table 6.3 95 Percent Confidence Intervals for Population Correlation Coefficients of Rigid Pavement Cases

Highway Route	Coefficient of Correlation R	Confidence Interval Lower Limit	Upper Limit
I-94	-0.7844	-----	-----(*)
I-65	-0.9839	-0.998	-0.856
I-69	-0.7771	-0.962	-0.772
I-70	-0.5222	-0.908	0.342
I-74	-0.8142	-0.969	0.201
I-64	-0.9381	-----	-----(*)

(*) Confidence intervals are not given for cases with 3 or less data points

Due to the small number of data points used in many of the cases considered in this study, the interval estimates were generally quite wide. These results clearly indicate the need to increase the number of data points in each of the cases analyzed.

Based upon the findings presented above, the following observations can be made:

a. The linearity assumption was only an approximation to the unknown real relationship between pavement performance and level of pavement routine maintenance. The results did not show a strong linear relationship between PSI-ESAL loss and maintenance expenditure per lane-mile for all the cases analyzed. The small number of data points available in the analyses had, to a great extent, weakened the power of the statistical tests performed and the conclusions drawn. Further research is needed to develop better representation of the relationship between pavement performance and routine maintenance.

b. More than one-third of the cases analyzed had four or less data points. The results suggested that desirably five or more data points be used for each highway route. To increase the number of data points in each highway route, it would be necessary to compute route maintenance costs in smaller unit than the highway section defined in this study. Unfortunately, this refinement cannot be achieved with the present recording practice in Indiana as all routine maintenance information is currently recorded county by county for each route on the basis of highway sections.

CHAPTER 7

QUANTITATIVE MEASUREMENT OF ROUTINE MAINTENANCE EFFECTS ON PAVEMENT PERFORMANCE

7.1 Introduction

One of the major concerns of a pavement management system (PMS) is the programming of pavement investments for a network of roads so as to achieve the optimal results for the available funds. This process usually involves analyses of different maintenance strategies and tradeoff between pavement maintenance and rehabilitation expenditures [74]. In order to effectively evaluate the merits of various investment alternatives at both network and project levels, an important requirement is to be able to project future pavement performance for a given amount of maintenance budget assigned to the network in question [71,75].

This calls for a procedure to estimate the effect of a proposed maintenance policy or plan on the performance of the pavements concerned. Unfortunately, as pointed out in Chapter 6, relationships between pavement performance and level of pavement routine maintenance have not yet been well developed. Most existing damage models do not consider the effects of pavement maintenance. Those that do, such as the EAROMAR system [12], are highly involved in their analyses and require a large amount of data. They do not provide a practical relationship which can be incorporated easily and effectively in the overall pavement performance assessment at network level.

This chapter presents a procedure to measure the effect of routine maintenance on pavement performance. The concept of the aggregate performance approach described in Chapter 3 provides the theoretical basis for this procedure.

7.2 A Concept of Measuring Pavement Routine Maintenance Effectiveness

7.2.1 General Background

The definition of maintenance varies among highway agencies. Maintenance work has been defined in this study, as implied in Section 4.2.4 and Table 4.9, as activities which are carried out routinely to maintain a pavement at or above a planned level of performance. These activities are usually performed in discontinuous sections. They do not include rehabilitation work, such as overlay and resurfacing, which serves to restore the serviceability of the pavement concerned to its original as-constructed level.

In terms of the terminology of aggregate performance approach as depicted in Figure 7.1, maintenance work refers to those activities that are carried out to 'recover' the PSI-ESAL loss between curves 4 and 1. The PSI-ESAL loss recovered by rehabilitation work is represented by the area between curves 1 and 3. Maintenance activities therefore have the effect of upgrading the pavement performance curve from the zero-maintenance curve (curve 4) to the field performance curve (curve 1) which represents the physical states of the pavement as measured by a field condition survey.

7.2.2 Effect of Levels of Routine Maintenance

In Chapter 3, it was assumed that on a homogeneous stretch of highway pavement, the level of pavement performance would be positively related to the extent of pavement routine maintenance. This assumption has been found to be valid for all the cases of Indiana highway routes analyzed in Chapter 6. A schematic representation of this concept was presented in Figure 3.7.

Figure 7.2 illustrates the same concept in terms of PSI-ESAL losses and routine maintenance expenditure per lane-mile. These two quantities represent the pavement

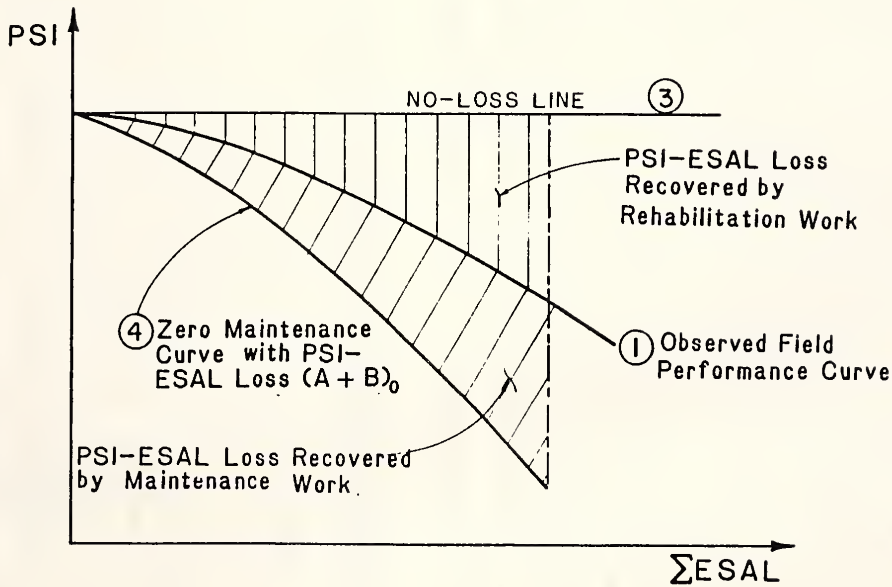
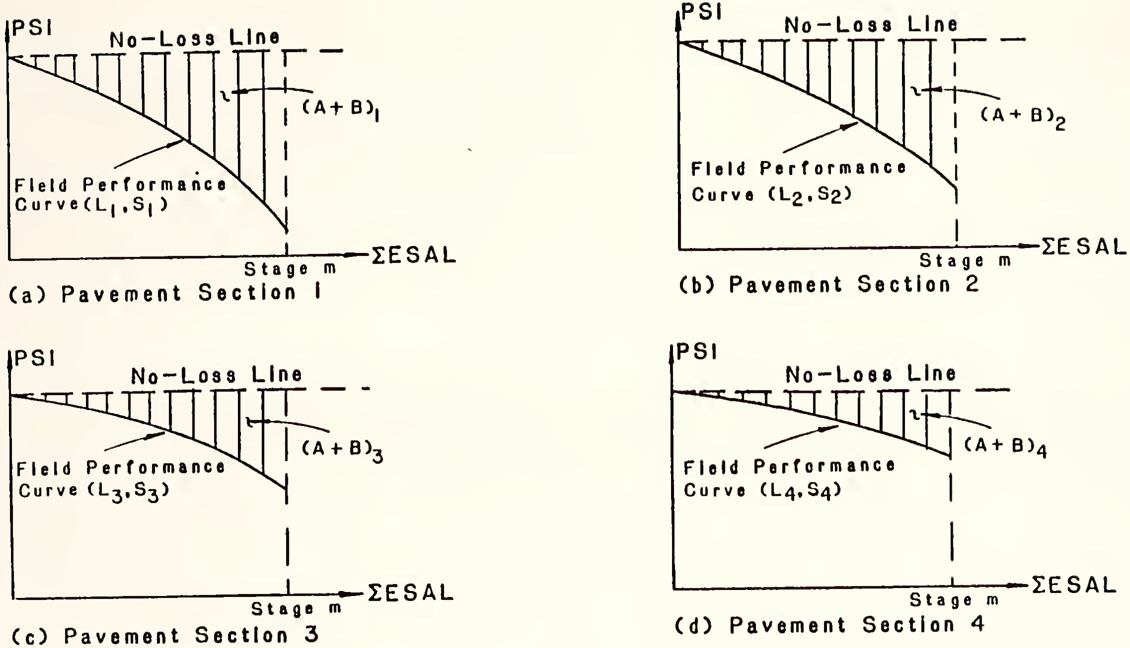


Figure 7.1 Schematic Diagram Showing the Effects of Pavement Routine Maintenance and Rehabilitation on Pavement Performance



LEGEND :

L_i = Level of Routine Maintenance on Pavement Section i

S_i = Routine Maintenance Expenditure per Lane-mile of Pavement Section i

$(A + B)_i$ = PSI-ESAL Loss of Pavement Section i at Stage m

Figure 7.2 Effect of Different Levels of Routine Maintenance on Pavement Performance damage and level of maintenance respectively for the pavement concerned. Four different levels of maintenance may be performed on four sections of the homogeneous pavement. The concept mentioned implies that,

$$S_4 > S_3 > S_2 > S_1 \quad (7.1)$$

and

$$(A+B)_1 > (A+B)_2 > (A+B)_3 > (A+B)_4 \quad (7.2)$$

where all the PSI-ESAL losses (A+B) are evaluated at the same cumulated ESAL value given by stage m.

The four performance curves in Figure 7.2 may be plotted in the same figure as shown in Figure 7.3. Also indicated in this figure is the zero-maintenance curve which could be derived from the four performance curves and their associated maintenance expenditures by means of the procedure described in Section 3.4.

Area k_1 in Figure 7.3 represents the amount of pavement damage recovered by spending S_1 dollars per lane-mile on routine maintenance. The corresponding recovered pavement damages for spending S_2, S_3 and S_4 dollars per lane-mile are (k_1+k_2), $(k_1+k_2+k_3)$ and $(k_1+k_2+k_3+k_4)$. Each of the areas k_i in Figure 7.3 gives the amount of PSI-ESAL loss reduction when a higher level of routine maintenance is adopted. For example, when a level of maintenance (L_2, S_2) is applied instead of a

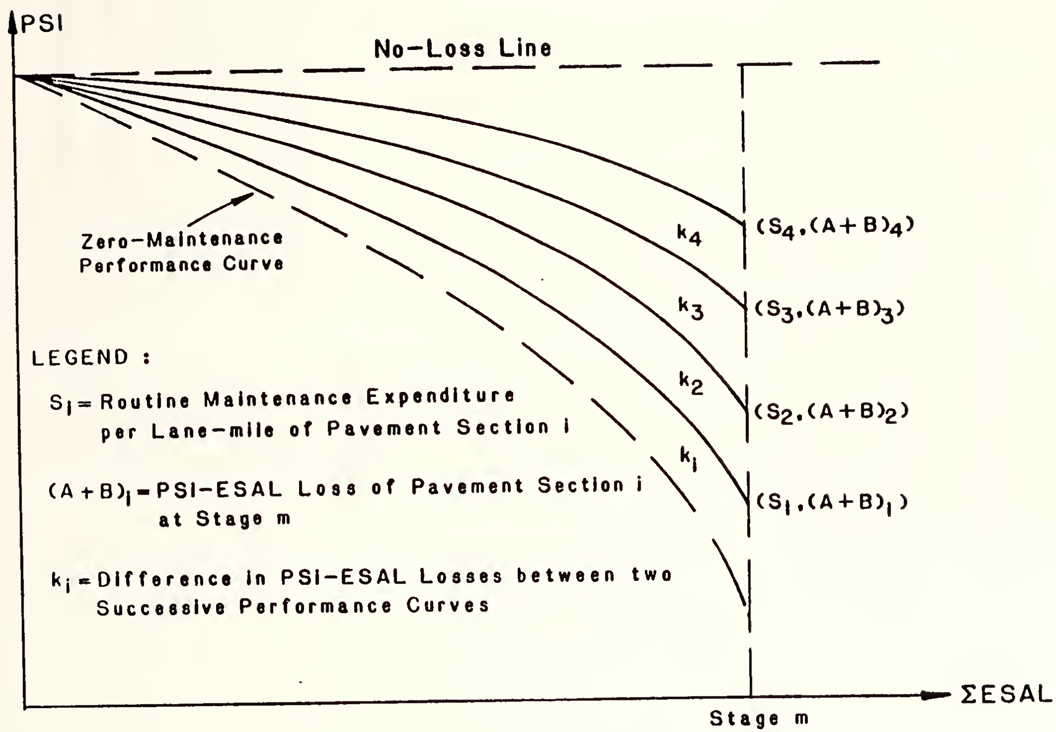


Figure 7.3 Comparison of Performance of Pavement Sections Maintained by Different Levels of Routine Maintenance

level (L_1, S_1), an improvement in pavement performance would materialize because the total PSI-ESAL loss would be reduced by an amount equal to k_2.

A measure of pavement routine maintenance effect on pavement performance may now be introduced. Consider again the two performance curves associated with maintenance expenditures S_1 and S_2. The effect of each dollar spent on maintenance may be expressed as an index M as follows:

$$M_{1,2} = \frac{k_2}{S_2 - S_1} \tag{7.3}$$

or

$$M_{1,2} = \frac{(A+B)_1 - (A+B)_2}{S_2 - S_1} \tag{7.4}$$

where $M_{1,2}$ represents the reduction in PSI-ESAL loss for each dollar spent between routine maintenance levels L_1 and L_2. The index M has the unit of PSI-ESAL loss/dollar/year/lane-mile. Other symbols in Equations (7.3) and (7.4) are defined in Figures 7.2 and 7.3.

It is interesting to note that the index M may be obtained by plotting PSI-ESAL loss (A+B) against routine maintenance expenditure per lane-mile, S, which happens to be the same plot (as illustrated in Figure 4.4) used for the damage analysis described in Chapters 4 and 5. The M value is simply the slope of such a plot. By fitting a straight line to the entire range of S values, the index M becomes an average unit measure of the effect of routine maintenance for the highway route considered.

7.2.3 Effects of Maintenance Policy and Technology

Highway pavement maintenance policy varies widely from agency to agency. This is due partly to the fact that pavement maintenance is performed for the most part by various highway agencies' own force, and partly to the diversified nature of routine maintenance activities. Different highway agencies do not place the same emphasis or weight on a given distress type in their maintenance programming and decision process [13,71]. This has led to different maintenance strategies adopted and different maintenance activities performed on pavements which are structurally similar.

In the aspect of maintenance technology, there are also disparities among different highway agencies. The common equipment available commercially are mostly designed to give quantity production for large scale construction projects. Maintenance operations, on the other hand, involve small crew size and small outputs at widely separated locations. As a result, many highway agencies have developed their own procedures and employ different equipment. Many maintenance policies or activities have been tried and adopted without adequate proof of their applicability or value [51,76,77].

Different maintenance policies and technology are likely to produce different results. Their effects on pavement performance are illustrated schematically in Figure 7.4, with all other conditions (climatic, environmental, and pavement characteristics) being equal. For easy explanation, consider an ideal case with the following conditions:

$$R_1 = S_1, \quad R_2 = S_2, \quad \text{and } R_3 = S_3 \; ; \tag{7.5}$$

and

$$p_1 > q_1, \quad p_2 > q_2 \tag{7.6}$$

A comparison is then possible by considering the index M defined in Section 7.2.2.

For maintenance policy and technology 1,

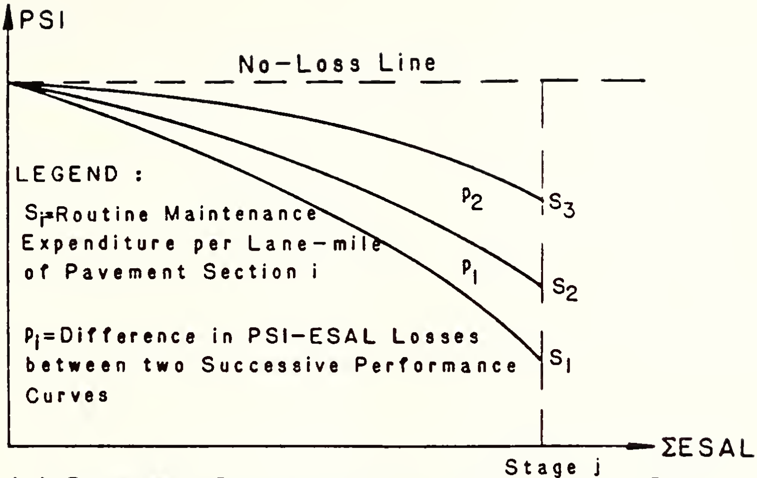
$$M_{1,2} = \frac{p_1}{S_2 - S_1} \tag{7.7}$$

$$M_{1,2} = \frac{p_2}{S_3 - S_2} \tag{7.8}$$

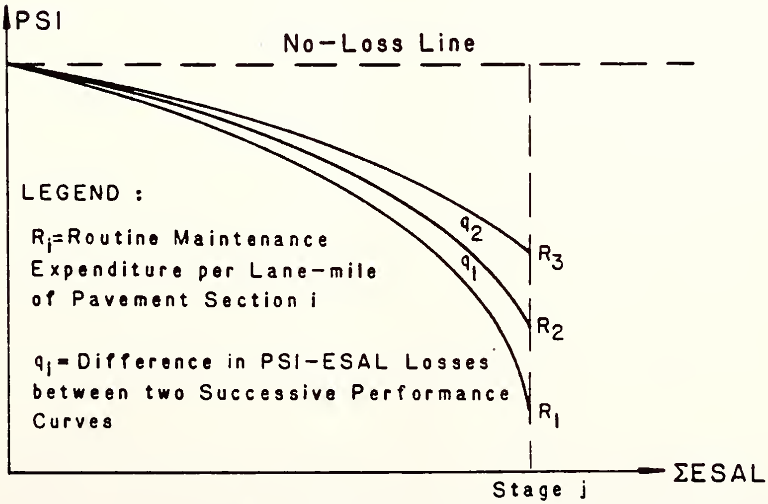
For maintenance policy and technology 2,

$$M_{1,2}' = \frac{q_1}{R_2 - R_1} \tag{7.9}$$

$$M_{2,3}' = \frac{q_2}{R_3 - R_2} \tag{7.10}$$



(a) Pavement Performance for Maintenance Policy and Technology 1



(b) Pavement Performance for Maintenance Policy and Technology 2

Figure 7.4 Effect of Maintenance Policy and Technology on Pavement Performance

The conditions in Equations (7.5) and (7.6) lead to the condition that $M_{1,2} > M'_{1,2}$, and $M_{2,3} > M'_{2,3}$. This conclusion implies that maintenance policy and technology 1 results in more reduction in PSI-ESAL loss. It can therefore be considered as more effective than maintenance policy and technology 2.

The discussion in this and the preceding section indicates that the index M can be considered as a measure of the effectiveness of pavement routine maintenance in recovering PSI-ESAL loss. It is therefore appropriate to term the index M as a pavement routine maintenance effectiveness index. It provides a means to evaluate the improvement in pavement performance that can be effected by routine maintenance work.

It should be pointed out that the order of magnitude of the effectiveness index M would vary according to the magnitude of cumulative ESAL at which M is evaluated. This means that when the magnitude of an effectiveness index M is mentioned, it is meaningful only if the associated cumulative ESAL level is specified.

7.2.4 Application of Pavement Routine Maintenance Effectiveness Index M

Two possible applications of the effectiveness index M are apparent from the discussions above. They are:

a. Evaluation of the effectiveness of existing maintenance policy and technology in improving pavement performance.

b. Comparison of the effectiveness of different maintenance policies and technology.

The data of Indiana highways used for damage responsibility analysis in Chapters 4 and 5 were again used as a case study to illustrate how the first application could be employed to produce useful information. The results of this application are presented in Section 7.3.

An illustration of the second application could not be performed because only Indiana data were available in this study. Instead, a brief outline of how such an application may be made is presented below.

Assuming that a highway agency is interested in finding out, from two or more maintenance policies or procedures, the policy or procedure that is best suited for the local conditions of interest. Several highway routes may be chosen for this purpose, and different maintenance procedures applied on different highway sections of each route. Within each highway section, it is necessary to subdivide into a few pavement subsections so that different levels of maintenance may be specified.

This would enable a performance plot such as those in Figure 7.4 to be prepared.

An analysis period must then be specified. A service period between two successive rehabilitation projects appears to be a logical choice. However, evaluation may be carried out at any stage within the analysis period as desired. It is quite possible that certain maintenance procedures are more effective on a short term basis, while others are superior in the long run. Comparison based upon maintenance index M is likely to reveal these differences.

Two points are worth mentioning in this analysis. Firstly, it is not necessary to use identical magnitudes of expenditure per lane-mile for different maintenance procedures. It would be impractical and unrealistic to impose such a control. Secondly, PSI loss alone does not give a valid comparison unless it is related to maintenance expenditures.

7.3 Pavement Maintenance Effectiveness Index M for Indiana Highways

The results of performance analysis on Indiana highways conducted in Chapter 4 can be used directly to derive the pavement routine maintenance effectiveness index M for each highway route. The value of the index M was given by the slope of the PSI-ESAL loss versus maintenance expenditure per lane-mile plot. Some of these performance plots are presented in Figures A.1 through A.20 of the Appendix.

It is noted that while the slopes of all the performance plots were negative, the index M did not carry the negative sign. There should be no confusion because by definition, the effectiveness index refered to the reduction in PSI-ESAL loss for each dollar maintenance expenditure spent.

The values of index M for 69 flexible pavement and 6 rigid pavement cases are recorded respectively in Tables 7.1 and 7.2. For flexible pavements, the M values were evaluated at a cumulative ESAL level of 1.5×10^5. For rigid pavements, they were estimated at a cumulative ESAL value of 1.5×10^7. These cumulative ESAL levels are selected arbitrarily by referring to the median and mean values of cumulative ESAL values of flexible and rigid pavement cases. The 6 rigid pavements, being Interstate highways, carried greater traffic and were much older than most of the flexible routes. This explains the large difference between the two cumulative ESAL values.

A summary of the characteristics of the M index values for rigid and flexible pavements analyzed is given in Table 7.3. A big difference in the order of magnitude

Table 7.1 Pavement Routine Maintenance Effectiveness Indices for Flexible Pavements in Indiana

No	Highway Route	Effectiveness Index M	No	Highway Route	Effectiveness Index M
1	SR 1(n)	5.50	36	SR 39(n)	11.31
2	SR 1(s)	1.89	37	SR 39(s)	4.02
3	SR 2	26.22	38	US 40	7.18
4	SR 3(n)	20.18	39	US 41	3.20
5	SR 3(s)	12.49	40	SR 42	1.50
6	SR 4	23.71	41	SR 43(n)	10.41
7	SR 5	26.93	42	SR 43(s)	3.00
8	US 6	11.90	43	SR 44	10.61
9	SR 8	32.72	44	SR 46	10.22
10	SR 9(n)	11.11	45	SR 47	14.29
11	SR 9(s)	14.38	46	SR 48	16.48
12	SR 10	20.38	47	US 50	5.21
13	SR 13	16.41	48	US 52(n)	5.89
14	SR 14	2.80	49	US 52(s)	10.80
15	SR 16	24.32	50	SR 55	7.60
16	SR 17	29.78	51	SR 56	3.09
17	SR 18	6.70	52	SR 57	13.22
18	SR 19	13.32	53	SR 58	14.88
19	US 20	14.81	54	SR 60	15.68
20	SR 23	16.01	55	SR 62	4.50
21	US 24	8.79	56	SR 63	12.72
22	SR 25	22.78	57	SR 64	11.01
23	SR 26	22.91	58	I 64	11.48
24	SR 28	12.39	59	I 65(s)	6.50
25	SR 29	10.59	60	SR 67	11.47
26	US 30	17.61	61	SR 75	8.50
27	US 31(n)	20.23	62	SR 135	10.61
28	US 31(s)	4.19	63	US 150	5.40
29	SR 32	5.10	64	US 231(n)	8.51
30	SR 33	19.57	65	US 231(s)	6.62
31	US 35	12.79	66	SR 234	10.68
32	US 36	10.38	67	SR 236	6.60
33	SR 37(n)	8.31	68	US 421(n)	10.09
34	SR 37(s)	2.82	69	US 421(s)	7.70
35	SR 38	16.29			

Note : 1. M is in PSI-ESAL Loss/dollar/year/lane-mile .
2. All M values are avaluated at cumulative Esal value of 150,000 .

Table 7.2 Pavement Routine Maintenance Effectiveness Indices for Rigid Pavements in Indiana

Serial Number	Highway Route	Effectiveness Index M ($\times 10^4$)
1	I-94	1.65
2	I-65	1.43
3	I-69	0.53
4	I-70	0.96
5	I-74	0.70
6	I-64	0.97

Note : 1. M is in PSI-ESAL loss/dollar/year/lane-mile .
2. All M values are evaluated at cumulative ESAl value of 15,000,000 .

Table 7.3 Characteristics of Pavement Routine Maintenance Effectiveness Indices for Indiana Highways

Description	Rigid Pavement	Flexible Pavement
No. of Cases Analysed	6	69
Cumulative ESAL Level at Analysis	1.5×10^{7}	1.5×10^{5}
Range of Effectiveness Index M (PSI-ESAL loss/$/year/lane-mile)		
Minimum	0.53×10^{4}	1.50
Maximum	1.65×10^{4}	32.70
Mean	1.04×10^{4}	11.99
Standard Deviation	0.43×10^{4}	0.85

was found between the M index values of flexible and rigid pavements. Although a direct comparison of the PSI-ESAL loss of the two pavement types was inappropriate, the reasons for the difference are believed to be: (i) the M values for the two pavement types were evaluated at different cumulative ESAL levels; and (ii) all the 6 rigid pavement cases were Interstate highways, whereas the flexible pavements were basically state routes. Furthermore, there is a difference in terms of design, construction and maintenance standards.

7.4 Regional Effects on Maintenance Effectiveness

The effects of climatic factors on the effectiveness of routine maintenance work is an area where little research has been done. The pavement routine maintenance effectiveness index proposed in this study provides a convenient means for measuring such effects quantitatively.

The same two regions in Indiana defined in Section 5.5 were used in the following analysis of regional effects on maintenance effectiveness. The same pavement characteristics and traffic loading variables identified in Section 5.2 were included in this analysis. A regression technique similar to that adopted in the analysis of pavement damage responsibility in Section 5.5

was employed. The relevant regression model is shown below:

$$M_i = c_0 + c_1 Z_i + c_2 X2_i + c_3 X3_i + c_4 X4_i + c_5 X5_i + c_6 X25_i + e_i \quad (7.11)$$

$$i = 1, 2, \ldots., n$$

where

M = pavement routine maintenance effectiveness index in PSI-ESAL loss/dollar/year/lane-mile

Z = 0 for southern region
1 for northern region

X2 = pavement age in years

X3 = slab thickness in inches for rigid pavement; structural number for flexible pavement

X4 = mean AADT

X5 = mean annual ESAL

X25 = total cumulative ESAL

e = random error term

c_k = regression parameters, k=1, 2, ..., 6

n = total number of data points

Separate regression analyses were performed for flexible and rigid pavements respectively to test the significance of regional effect in each case. The results of these analyses are discussed in the following sections.

7.4.1 Analysis of Flexible Pavements

The regional distribution of pavement maintenance effectiveness index values for flexible pavements is depicted in Figure 7.5. Each effectiveness index value was plotted at the mid point of the highway route for which the index was derived. Each mid point location is represented in Figure 7.5 as the distance in miles measured from Owensboro, a town situated at the southern border of Indiana. The plot indicates that there is relatively little variation of the effectiveness index values for highway routes located within approximately 180 miles from Owensboro. However, moving northward from this distance, it appears that there exists a trend showing higher effectiveness index values for highway routes located further away from Owensboro in the northerly direction.

The results of statistical analysis for the effectiveness index values of flexible pavements based upon the model in Equation (7.11) is summarized in Table 7.4. The regional effect was found to be significant at both 0.05 and 0.01 level of significance, meaning that pavement routine maintenance effectiveness on flexible pavements was significantly different statistically in the two regions.

These results led to the conclusion that pavement

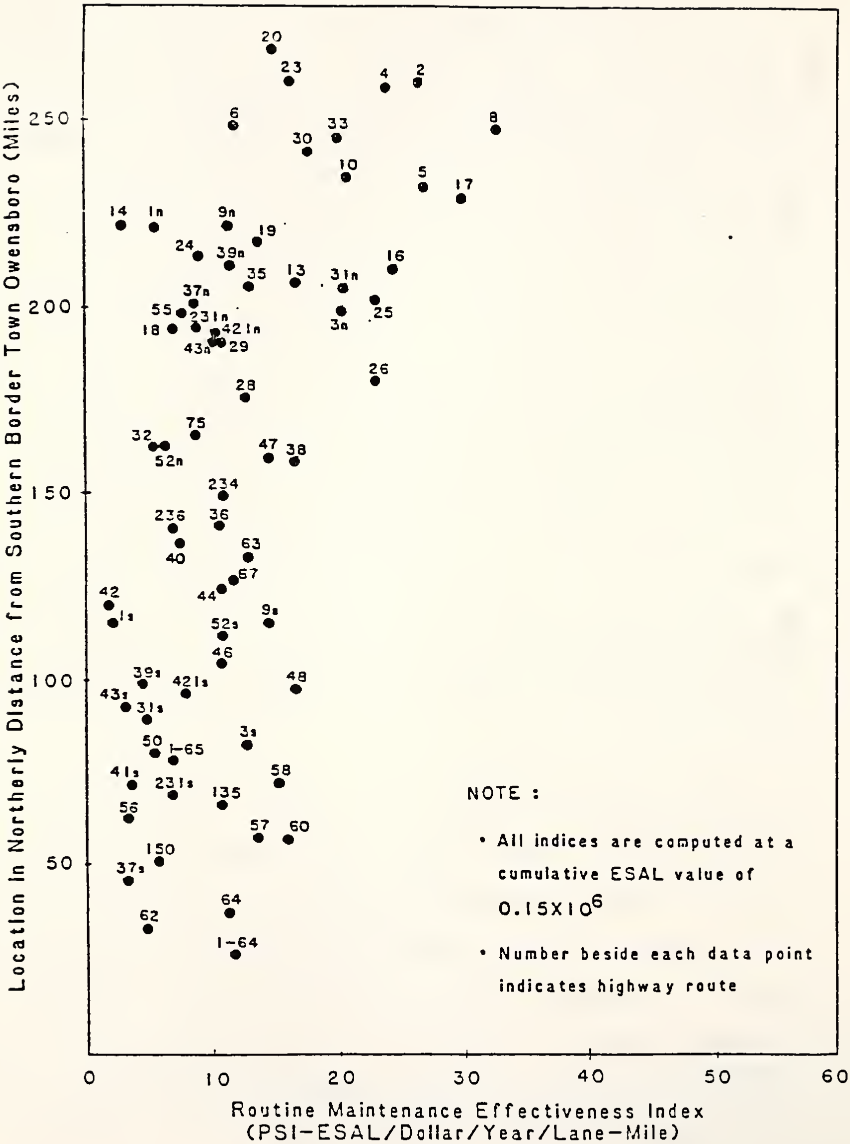


Figure 7.5 Regional Distribution of Pavement Maintenance Effectiveness Index on Flexible Pavements in Indiana

Table 7.4 Statistical Analysis for Model in Equation (7.11) ---- Flexible Pavement

(a) Regression Analysis

Coeff.	Estimated Value	Standard Deviation	t Value
c_0	47.192	13.775	3.426
c_1	7.424	1.450	5.118(*)
c_2	-1.271	0.288	-4.412
c_3	-5.037	2.661	-1.893
c_4	-0.0002	0.0004	-0.464
c_5	- 18.764	19.072	-0.984
c_6	-2.935	2.760	-1.063

(*) significant at lavels 0.05 and 0.01

(b) Analysis of Variance

Source of Variation	Sum of Squares	df	MS
Regression	1410.85	6	235.14
Error	1962.60	62	31.66
Total	3373.45	68	

routine maintenance effectiveness index was higher in the northern region than in the southern region. Physically, it means that the amount of pavement damage repaired (i.e. the amount of PSI-ESAL loss recovered) per dollar worth of maintenance work was greater in the northern region. In other words, it may be said that each dollar of maintenance expenditure spent per lane-mile in the northern region was more effective than in southern region in improving pavement performance.

7.4.2 Analysis of Rigid Pavements

As there were only six rigid pavement cases available, a reduced version of the general model in Equation (7.11) was used for the analysis presented in this section. Since the several reduced models selected all led to the same conclusion regarding the regional effect on maintenance effectiveness, only one of them is presented below for the purpose of discussion. The model with the best R^2 and adjusted R^2 values is:

$$Y2_i = c_0 + c_1 Z_i + c_2 X2_i + e_i \tag{7.12}$$

where all terms are defined as in Equation (7.11).

The results of statistical analysis are presented in Table 7.5. It was found that regional effect was significant only at a level of significance of 0.431. It may therefore be concluded that there is no difference

Table 7.5 Statistical Analysis for Model in Equation (7.12) ---- Rigid Pavement

(a) Regression Analysis

Coeff.	Estimated Value	Standard Deviation	t Value
c_0	25942.82	8701.22	2.982
c_1	2439.30	2689.05	0.907(*)
c_2	-1034.76	511.91	-2.021

(*) significant at lavel 0.431

(b) Analysis of Variance

Source of Variation	Sum of Squares	df	MS
Regression	59351738	2	29675869
Error	31772065	3	10590688
Total	91123803	5	

between the maintenance effectiveness indices in the two regions.

7.5 Pavement Routine Maintenance Effectiveness Index Prediction Models

The indicator variable Z was used in Equations (7.11) and (7.12) for testing the influence of regional effect on pavement maintenance effectiveness. It is, however, not an ideal variable to be included in a prediction model for the following reasons. Firstly, it does not have a clear meaning as it is not possible to define quantitatively the criteria used to delineate the two regions. Secondly, being qualitative in nature, variations in conditions within each of the two regions are not reflected. As each region covers a big area and a large number of highway routes, a model expressed as a function of regional variable Z does not provide a prediction sufficiently specific and accurate for most applications. To produce results which are practically meaningful, it is therefore desirable to develop prediction models upon independent variables that can be measured physically and are directly related to the conditions of each highway route.

Regression models were consequently developed for the purpose of predicting pavement maintenance effectiveness index M. The independent variables considered for inclusion in these prediction models were those discussed in Section 5.3 and listed in Table 5.3. Potential uses of these models are first discussed, followed by presentation of the results of regression analyses for flexible and rigid pavements.

7.5.1 Uses of A Maintenance Effectiveness Prediction Model

Information that can be derived from a prediction model of pavement routine maintenance effectiveness index may be of use in the following areas:

a. Highway programming -- A highway program should ideally be based upon information gathered from condition surveys which reveal the status of pavements and the locations of deficient sections. Specific information concerning pavement performance and maintenance can be vital in order to arrive at an acceptable budget plan. Prediction of maintenance effectiveness indices for different pavement sections can be a useful aid to budget planning by providing a means for quick evaluation of network performance at different levels of maintenance funding.

b. Allocation of Maintenance Funds -- A common problem faced by pavement maintenance managers nowadays is how to spend optimally their limited amount of maintenance dollars. A maintenance fund allocation problem is not limited to a clear cut solution of to maintain or not to maintain. More importantly, it involves, most of the time, the decision of how much maintenance to be carried out at each location to achieve the best overall results at network level. Routine maintenance effectiveness index may be used in this process as a ready evaluation tool for assessing the relative credit of each maintenance strategy.

c. Pavement Conditions Projection -- The knowledge of maintenance effectiveness index enables projection of pavement conditions to be made on an individual highway route based on the amount of maintenance fund allocated to it. This analysis may be carried out at both project and network levels.

d. Updating Network Improvement Programs -- Pavement maintenance effectiveness index provides a convenient quantitative measure for evaluating the effectiveness of past maintenance works. This evaluation provides valuable maintenance feedback information which could be used for improving and updating the existing network improvement program.

7.5.2 Models for Flexible Pavements

The correlation matrix which shows the coefficients of correlation for all pairs of dependent and independent variables are given in Table 7.6. The following observation can be made from the correlation matrix: (i) Of all the climatic and environmental variables, soil support value (X12) could best explain the variation in maintenance effectiveness index M. (ii) In general, individual climatic variables correlate better with M than pavement characteristics or traffic loading data.

Two regression models for flexible pavement are presented in this discussion. The first model is expressed in terms of climatic and pavement characteristic variables, while the second model in terms of soil support value and a pavement characteristic variable. These models are given in Equations (7.13) and (7.14) below.

$$M = 41.536 + 0.0264(X6) - 1.049(X2) - 4.615(X3) \quad (7.13)$$

$$M = -36.165 + 9.589(X12) - 0.296(X2) \quad (7.14)$$

where

M = pavement routine maintenance effectiveness index in PSI-ESAL/dollar/year/lane-mile

X2 = pavement age in years

Table 7.6 Correlation Matrix for Statistical Analysis of Maintenance Effectiveness for Flexible Pavements in Indiana

	Y2	X2	X3	X4	X5	X25	X6	X7	X8	X9	X10	X11	X12
Y2	--	-.345	-.017	-.022	-.086	-.083	.589	.565	-.519	-.474	-.469	-.505	.835
X2	-.345	--	-.376	-.211	-.157	-.053	-.055	.009	-.078	-.117	-.085	-.095	-.289
X3	-.017	-.376	--	.654	.283	.249	.119	.124	-.105	-.118	-.055	-.100	-.024
X4	-.022	-.211	.654	--	.557	.553	.151	.112	-.053	-.041	-.077	-.039	-.022
X5	-.086	-.157	.283	.557	--	.951	-.131	-.177	.222	.228	.143	.229	-.112
X25	-.083	-.053	.249	.553	.951	--	-.113	-.170	.223	.229	.070	.232	-.124
X6	.589	-.055	.119	.151	-.131	-.113	--	.971	-.905	-.835	-.821	-.884	.737
X7	.565	.009	.124	.111	-.177	-.170	.971	--	-.975	-.937	-.868	-.962	.699
X8	-.519	-.078	-.105	-.053	.222	.223	-.905	-.975	--	.984	.870	.999	-.624
X9	-.475	-.117	-.119	-.041	.228	.228	-.835	-.937	.984	--	.880	.989	-.564
X10	-.469	-.085	-.055	-.077	.143	.070	-.821	-.868	.870	.880	--	.868	-.556
X11	-.505	-.095	-.100	-.039	.229	.232	-.884	-.962	.999	.989	.868	--	-.602
X12	.835	-.287	-.023	-.022	-.112	-.124	.737	.700	-.625	-.564	-.556	-.602	--

X3 = pavement structural number

X6 = freezing index in degree F-days

X12 = soil support value

Physically interpretable interaction terms were included in the regression analysis, but were found to have very little effects on the resulting R^2 value. The terms considered included (i) interaction between a climatic or environmental variable and a pavement characteristic variable; (ii) interaction between a climatic or environmental variable and a traffic loading variable; (iii) interaction between a pavement characteristic and a traffic loading variable; and (iv) interaction between soil support value and climatic variables.

The regression analysis results for the two models in Equations (7.13) and (7.14) are presented in Table 7.7. On the basis of the magnitude of R^2 value, the model in Equation (7.14) is superior. It is noted that in this model, the soil support value alone could account for 69.6% of the variation in the index M.

7.5.3 Models for Rigid Pavements

For the rigid pavements analyzed in this study, pavement characteristic variable (only data on pavement age were available), traffic loading variables and soil

Table 7.7 Statistical Characteristics of Maintenance Effectiveness Index Models for Flexible Pavements in Indiana

Description	Model (7.13)	Model (7.14)
Independent Variables	X6, X2, X3	X12, X2
No. of Data Points	69	69
Coeff. of Multiple Determination	0.4937	0.7082
Linearity Test		
F value	21.13	80.07
α level	0.000	0.000
Test for Coefficients		
Variable 1	X6	X12
F value	44.91	133.24
α level	0.000	0.000
Variable 2	X2	X2
F value	17.81	2.67
α level	0.000	0.107
Variable 3	X3	
F value	6.22	---
α level	0.015	

Note : Maintenance effectiveness index is evaluated at a cumulative ESAL value of 150,000 .

support value all provided reasonably good correlation with pavement maintenance effectiveness index M. Climatic variables were less capable of explaining the variation in the effectiveness index. The above observations were derived from the correlation matrix presented in Table 7.8.

Using a level of significance of 0.05 as the criterion, the 'best' regression model obtained with the SPSS stepwise regression search method [49] is given below.

$$M = 7316.40 + 0.0239(X5) - 0.001341(X25) \quad (7.15)$$

where

X5 = mean annual cumulative ESAL

X25 = total cumulative ESAL

The detailed characteristics of this model is found in Table 7.9. The variable X25 represents the interaction between pavement age (X2) and mean annual traffic loading level (X5).

An alternative prediction model is also presented in Table 7.9. This model is expressed as a linear regression function of soil support value (X12) and pavement age (X2). The R^2 value of this model is lower, but can still be considered as satisfactory.

Table 7.8 Correlation Matrix for Statistical Analysis of Maintenance Effectiveness for Rigid Pavements in Indiana

	Y1	X2	X4	X5	X25	X6	X7	X8	X9	X10	X11	X12
Y1	—	-.745	.797	.801	.641	.528	-.318	.670	-.271	-.586	-.371	.781
X2	-.745	—	-.347	-.368	-.191	-.143	.009	-.279	-.236	.559	-.206	-.323
X4	.797	-.347	—	.994	.976	.896	.821	-.730	-.568	-.407	-.689	.920
X5	.801	-.368	.994	—	.980	.867	.814	-.729	-.595	-.366	-.704	.873
X25	.670	-.191	.976	.980	—	.874	.846	-.813	-.627	-.256	-.765	.841
X6	.641	-.143	.896	.867	.874	—	.956	-.854	-.726	-.604	-.813	.913
X7	.528	.009	.821	.814	.846	.956	—	-.950	-.897	-.480	-.944	.769
X8	-.318	-.279	-.730	-.729	-.813	-.854	-.950	—	.932	.196	.975	-.635
X9	-.272	-.236	-.568	-.595	-.657	-.726	-.897	.932	—	.212	.982	-.426
X10	-.586	.559	-.407	-.336	-.256	-.604	-.480	.196	.212	—	.226	-.590
X11	-.371	-.207	-.689	-.705	-.765	-.813	-.944	.975	.982	.226	—	-.568
X12	.781	-.323	.920	.873	.841	.913	.769	-.635	-.426	-.590	-.568	—

Table 7.9 Statistical Characteristics of Maintenance Effectiveness Index Models for Rigid Pavements in Indiana

Description	Model (7.13)	Model (7.14)
Independent Variables	X5, X25	X2, X12
No. of Data Points	6	6
Coeff. of Multiple Determination R^2	0.977	0.882
Adjusted R^2	0.962	0.803
Linearity Test		
F value	65.18	11.17
α level	0.003	0.041
Test for Coefficients		
Variable 1	X5	X2
F value	70.43	6.87
α level	0.004	0.079
Variable 2	X25	X12
F value	44.88	8.26
α level	0.007	0.064

Note : Maintenance effectiveness index is evaluated at a cumulative ESAL value of 15,000,000 .

7.6 Summary Remarks

The case study performed in this chapter indicates that the concept of performance analysis introduced in this research (see Chapter 3) can be further extended to provide a useful evaluation tool for assessing the quality and effectiveness of pavement maintenance work. Potential applications of the information obtainable with this analysis to various stages of a maintenance management process was discussed. However, more research is required before the technique presented can be effectively incorporated in a pavement management system.

The analysis on Indiana highways concluded that there was a significant difference in pavement routine maintenance effectiveness (as measured by the pavement maintenance effectiveness index M) between the flexible pavements in the northern and the southern regions. Further regression analyses also confirmed this finding that climatic and environmental variables were able to explain the variation in the maintenance effectiveness index reasonably well.

On the other hand, the analysis on the rigid pavements in Indiana revealed that the difference between the pavement maintenance effectiveness indices in the northern and the southern regions was statistically insignificant. Subsequent regression analyses showed that most of the variation in these effectiveness indices could be accounted for by considering pavement characteristic and traffic loading information, as well as the roadbed soil support values.

These findings agree well with those found in Chapter 5 where damage responsibilities on the two pavement types in Indiana were analyzed. This agreement should be within anticipation due to the fact that the same data base and inference space were used in both analyses, and that both procedures were developed on the same theoretical basis.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1 Summary of Proposed Performance Analysis Approach

The main objective of this study was to develop a methodology for highway pavement performance analysis by means of an aggregate pavement damage approach. The use of a disaggregate distress function approach would require a large amount of data collection and handling effort. In contrast, the data required for an aggregate performance are much less and are more readily available.

Central to the development of the aggregate performance approach methodology was the introduction of the following concepts:

1. PSI-ESAL Loss as A Representation of Pavement Deterioration -- Instead of using the parameter PSI loss traditionally used in pavement evaluation analysis, PSI-ESAL loss was proposed as a measure of pavement deterioration. By adding another dimension, the new parameter offers a quantitative

representation of pavement deterioration covering the entire pavement performance history.

2. Quantitative Representation of Levels of Pavement Routine Maintenance -- For a given maintenance policy and technology, it was possible to associate a level of pavement routine maintenance to each of the performance curves of different pavement sections of a highway route with uniform pavement characteristics. The levels of maintenance were defined by their respective average annual maintenance expenditure per lane-mile of the pavement section concerned.

3. Relationship between Pavement Performance and Level of Maintenance -- An assumption was made which stated that pavement performance was positively related to the level of routine maintenance. The two physical measures defined in items 1 and 2 above facilitated the establishment of a quantitative relationship between pavement performance and levels of pavement routine maintenance.

4. The Concept of Zero-Maintenance Pavement Performance -- The need to consider the effects of maintenance policy and maintenance activities on pavement performance was emphasized. The PSI-ESAL loss computed from the observed field performance curve of

a pavement does not represent the actual total damage that has taken place, as part of the pavement damage gets repaired by maintenance work. The concept of zero-maintenance pavement performance was introduced to estimate the total pavement damage.

Using the concepts presented above, a procedure was developed to calculate the relative pavement damage responsibilities of load-related and non-load-related effects. This procedure was based upon a comparison between actual field performance and the AASHTO pavement performance prediction.

A further development of performance analysis within the framework of the proposed aggregate performance approach involved a concept of measuring the effects of routine maintenance on pavement performance. A quantitative measure, known as the pavement routine maintenance effectiveness index, was introduced. Uses of this index in assessing the effects of pavement routine maintenance work, and in evaluating the effectiveness of different maintenance policies and strategies were discussed and illustrated.

8.2 <u>Summary of Findings</u>

All the analyses conducted in this study were performed with data from the state highway system of

Indiana. The major findings of these analyses are summarized below.

1. The pavement damage responsibility of load-related effects ranged from 71.3 to 100% for flexible pavements, and from 52.4 to 67.7% for rigid pavements. A direct comparison of the damage responsibility values of the two pavement types could not be made because the terms and formulas used to describe the load-related effects did not have identical physical meanings. Furthermore, all the rigid pavements analyzed were on Interstate highways, whereas the flexible pavements were predominantly state routes. There were large differences in both pavement age and total cumulative traffic loadings between them.

2. Two regional zones were defined for the State of Indiana. Statistical analyses showed that the non-load-related responsibilities on flexible pavements in the northern region were significantly higher than those in the southern region. In the case of rigid pavements, the difference between the damage responsibilities in the two regions were found to be statistically insignificant.

3. Pavement damage responsibility prediction models were developed for both flexible and rigid pavements.

Climatic variables explained reasonably well the variations in the damage responsibilities of flexible pavements, but did not do so satisfactorily for rigid pavements. Pavement age alone could account for about 86% of the variations in damage responsibilities on rigid pavements.

4. A pavement routine maintenance effectiveness index M was defined to measure the effects of maintenance on pavement performance. Significant difference was found between the values of effectiveness index for flexible pavements in the two regions in Indiana. However, the difference between the index M values of rigid pavements in the two regions was found to be statistically insignificant.

5. Regression analyses indicated that the effectiveness index M for flexible pavements could be predicted on the basis of climatic and environmental variables. On the other hand, in computing the effectiveness index on rigid pavements, better prediction could be obtained by considering traffic loading information, or roadbed soil support values and pavement characteristics. In general, the findings in items 4 and 5 were consistent with those in items 2 and 3.

6. The validity of the two assumptions made in the above analyses were examined in Chapter 6 with data from

Indiana highways. The results showed that the assumption which stated that level of routine maintenance was positively related to pavement performance was valid for all the cases analyzed, and that the assumption of linear relationship between these two measures was a reasonable approximation.

7. A main focus of this study was upon demonstrating the applicability of the aggregate performance approach to the performance analysis of highway pavement. One of the most significant findings of this study was therefore the confirmation of the feasibility of such an approach as an alternative to the much more elaborate disaggregate distress function approach methodologies.

8.3 Limitations of the Proposed Approach

The aggregate performance approach developed in this study has a number of limitations which are described briefly in the following paragraphs.

The approach, taking into account only the aggregate performance of pavements, does not provide information concerning detailed structural conditions of the pavements. It is quite possible that pavements with different structural characteristics may give comparable PSI-ESAL loss although the distress types involved are very different. This and other requirements have led to the limitation that each performance analysis be performed on a uniform highway route with homogeneous pavement characteristics.

In the case study of performance analysis on Indiana highways, the above limitation has in turn resulted in the problem of having relatively few data points in each analysis. The root of this problem lies in the fact that the routine maintenance expenditures in Indiana are recorded on the basis of highway sections bounded by county limits. This problem can be solved only if maintenance expenditures are recorded in smaller units than a highway section. In other words, the current practice of recording maintenance expenditures by county should be further refined. For instance, maintenance expenditures may be recorded in terms of highway contract section.

In employing the aggregate performance approach to estimate the pavement damage responsibilities of load-related and non-load-related effects, it should be realized that the relative responsibilities so determined represent an overall assessment of the damages recovered by both maintenance and rehabilitation. Applying these relative responsibilities to allocation of both maintenance and rehabilitation costs in a highway cost allocation study implies that for every unit of pavement damage the relative responsibilities of load-related and non-load-related effects remain the same. This may not be so in reality.

It is apparent from the sequence of testing involved in a pavement evaluation program that pavement performance information obtained from serviceability condition survey does not reveal pavement deficiency in skid resistance or other safety-related pavement defects. Since routine maintenance costs were used to define the level of maintenance of a given pavement performance, this means that the portion of maintenance costs that were used to correct safety-related defects without having any effects on pavement performance measurement should not be included in the analysis. Unfortunately, it was not possible to isolate this portion of the costs from the maintenance records in Indiana.

Several assumptions were made in the present study which could affect the results and their interpretation. An example is the linear relationship between level of pavement routine maintenance and pavement performance. Another example is the proportionality assumption used in calculating the pavement damage responsibilities of load-related and non-load-related effects. These assumptions were necessary as the state-of-the-art knowledge in these areas did not allow the development of any quantitative relationship which could be used in this study.

8.4 Recommendations for Further Research

Pavement performance data are an integral part of the data base for a pavement management system. The availability of these data is becoming increasingly common in highway agencies across the nation. The performance analysis methodology presented in this study reveals that the usefulness of these data has not been fully exploited. Based upon the findings of this study, further research in the following areas is recommended.

The relationship between pavement maintenance and performance has not been well established. The linear relationship between levels of pavement routine maintenance and pavement performance adopted in the performance analysis in this study is purely a result of regression analysis based upon limited data from highways in Indiana. To provide the necessary data for establishing the relationship desired, a detailed record of maintenance activities and maintenance costs must be available. For instance, in the case of Indiana, it is recommended that maintenance activities be recorded in detail in smaller pavement section unit than the highway section currently used.

A linear proportionality assumption was used to estimate the relative pavement damage responsibilities of load-related and non-load-related effects. Research on the interactive effect between load and environmental factors on pavement damage would have wide implications not limited only to the field of highway cost allocation. It can probably best be determined by long term monitoring of pavement performance over a wide range of load, climatic and environmental conditions.

One of the limitations of the aggregate performance approach is that it does not reveal any specific pavement defect information. On the other hand, one of the biggest problem with disaggregate distress function approach procedures has been to relate individual pavement distress types to overall pavement performance. The pavement routine maintenance effectiveness index M introduced in this study may be able to provide a partial solution to this problem.

This study has demonstrated with a case study how a quantitative relationship between pavement performance and levels of pavement routine maintenance could be developed. This relationship is characterized by the index M which gives the slope of the relationship. This index measures the effectiveness of a given maintenance work in improving the performance of the pavement concerned. If it is possible to identify the type of pavement distress by relating them to the effectiveness index, then a meaningful relationship between distress types and pavement performance may be established.

The theoretical framework of the aggregate performance approach presented in this study could provide a means for establishing such a link between pavement performance and distress types. Since only pavement sections with homogeneous pavement characteristics are included in each independent performance analysis of a highway route, it is quite likely that the dominating distress pattern would be similar on these pavement sections. Once this distress pattern is identified, it may be related to the effectiveness index computed from the performance analysis.

As can be seen from the flow diagram in Figure 2.1, identification of distress pattern may be obtained from a level II pavement condition survey. This clearly shows that such an analysis can be carried out with data which are already available in a typical pavement management program. No additional data collection effort is needed. This also indicates that once a pavement management system is in operation, the performance analysis proposed in this study and the further analysis recommended in this section can be incorporated into the system to provide additional information which could be useful to decision-makers at both network and project levels.

Finally, it should be mentioned that pavement performance analysis should not be considered as a one-time exercise. It should be recognized as a part of a continuing process of pavement management. A periodic updating of the damage responsibilities of load-related and non-load-related effects, and the pavement maintenance effectiveness indices, as well as the prediction models for these parameters is needed in order to keep abreast with the changing traffic distributions, changing expenditure pattern, changing emphasis, and changing technology. In addition, improvement to the procedure and methodology presented in this study should be made from time to time as new information on such key elements as relationships between traffic, weather, and pavement damage is available from further research.

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APPENDIX

Some Results of Performance Analysis on Indiana Highways

Table A.1 Results of Correlation Analysis between PSI-ESAL Loss and Mean Annual Maintenance Expenditure Per Lane Mile on Rigid Pavements

S/No	Highway Route	Data Points	Coeff. R	Coeff. R^2	Adjusted R^2	Linearity Test	
						t Value	α Level
1	I-94	3	-0.7844	0.6153	0.2310	-1.599	0.40
2	I-65	6	-0.9839	0.9681	0.9601	-11.020	0.05
3	I-69	8	-0.7771	0.6039	0.5379	-3.025	0.05
4	I-70	8	-0.5222	0.2727	0.1515	-1.502	0.20
5	I-74	8	-0.8142	0.6629	0.6067	-3.435	0.05
6	I-64	3	-0.9381	0.8801	0.7601	-2.708	0.25

Table A.2 Results of Correlation Analysis between PSI-ESAL Loss and Mean Annual Maintenance Expenditure Per Lane Mile on Flexible Pavements

S/No	Highway Route	Data Points	Coeff. R	Coeff. R^2	Adjusted R^2	Linearity Test t Value	Linearity Test α Level
1	SR 1(n)	4	-0.7847	0.6158	0.4237	-2.193	0.15
2	SR 1(s)	5	-0.7989	0.6382	0.5189	-1.881	0.20
3	SR 2	4	-0.8238	0.6787	0.5181	-2.055	0.20
4	SR 3(n)	6	-0.8749	0.7655	0.7069	-3.614	0.05
5	SR 3(s)	5	-0.8931	0.7976	0.7301	-3.438	0.05
6	SR 4	3	-0.8981	0.8065	0.6130	-2.042	0.30
7	SR 5	3	-0.9600	0.9216	0.8432	-3.429	0.20
8	US 6	7	-0.8417	0.7085	0.6502	-3.486	0.05
9	SR 8	3	-0.9751	0.9508	0.9016	-4.396	0.15
10	SR 9(n)	6	-0.6507	0.4234	0.2793	-1.714	0.15
11	SR 9(s)	3	-0.8721	0.7606	0.5212	-1.782	0.35
12	SR 10	4	-0.8888	0.7900	0.6850	-2.743	0.15
13	SR 13	6	-0.8136	0.6619	0.5774	-2.798	0.05
14	SR 14	5	-0.8905	0.7930	0.7240	-3.390	0.05
15	SR 16	6	-0.8474	0.7181	0.6476	-3.192	0.05
16	SR 17	2	-1.0000	1.0000	----	----	----
17	SR 18	4	-0.8772	0.7695	0.6548	-2.584	0.15
18	SR 19	5	-0.7074	0.5004	0.3338	-1.733	0.20
19	US 20	5	-0.9108	0.8296	0.7728	-3.822	0.05
20	SR 23	2	-1.0000	1.0000	----	----	----
21	US 24	5	-0.9586	0.9189	0.8918	-5.830	0.05
22	SR 25	4	-0.7797	0.6079	0.4119	-1.760	0.25
23	SR 26	7	-0.9074	0.8234	0.7881	-4.828	0.05
24	SR 28	7	-0.7525	0.5663	0.4796	-2.555	0.05
25	SR 29	2	-1.0000	1.0000	----	----	----

Table A.2 (continued)

S/No	Highway Route	Data Points	Coeff. R	Coeff. R^2	Adjusted R^2	Linearity Test t Value	Linearity Test α Level
26	US 30	7	-0.9370	0.8780	0.8536	-5.999	0.05
27	US 31(n)	8	-0.8788	0.7723	0.7344	-4.511	0.05
28	US 31(s)	5	-0.9863	0.9728	0.9637	-8.458	0.05
29	SR 32	7	-0.7638	0.5834	0.5001	-2.646	0.05
30	SR 33	5	-0.7000	0.4900	0.3200	-1.698	0.20
31	US 35	7	-0.6728	0.4527	0.3432	-2.034	0.10
32	US 36	6	-0.7951	0.6322	0.5403	-2.622	0.10
33	SR 37(n)	3	-0.9601	0.9218	0.8436	-3.433	0.20
34	SR 37(s)	3	-0.9828	0.9659	0.9318	-5.322	0.15
35	SR 38	5	-0.8397	0.7051	0.6068	-2.678	0.10
36	SR 39(n)	4	-0.8812	0.7665	0.6498	-2.562	0.15
37	SR 39(s)	4	-0.8431	0.7120	0.5680	-2.224	0.20
38	US 40	4	-0.7380	0.5446	0.3169	-1.547	0.25
39	US 41	8	-0.5956	0.3548	0.2473	-1.816	0.15
40	SR 42	3	-0.7934	0.6295	0.2590	-1.843	0.20
41	SR 43(n)	2	-1.0000	1.0000	----	----	----
42	SR 43(s)	2	-1.0000	1.0000	----	----	----
43	SR 44	6	-0.8847	0.7827	0.7284	-3.796	0.05
44	SR 46	8	-0.6463	0.4177	0.3207	-2.075	0.10
45	SR 47	3	-0.6456	0.4168	0.1252	-0.845	0.50
46	SR 48	3	-0.9925	0.9851	0.9702	-8.131	0.10
47	US 50	5	-0.6930	0.4802	0.3069	-1.665	0.20
48	US 52(n)	8	-0.7346	0.5396	0.4629	-2.652	0.05
49	US 52(s)	2	-1.0000	1.0000	----	----	----
50	SR 55	5	-0.8835	0.7806	0.7075	-3.267	0.05

Table A.2 (continued)

S/No	Highway Route	Data Points	Coeff. R	Coeff. R^2	Adjusted R^2	Linearity Test t Value	Linearity Test α Level
51	SR 56	7	-0.6645	0.4416	0.3299	-1.988	0.10
52	SR 57	5	-0.5783	0.3344	0.1125	-1.228	0.25
53	SR 58	3	-0.8605	0.7405	0.4810	-1.689	0.35
54	SR 60	8	-0.6441	0.4149	0.3174	-2.063	0.10
55	SR 62	3	-0.8035	0.6456	0.2912	-1.350	0.40
56	SR 63	3	-0.9160	0.8391	0.6782	-2.284	0.30
57	SR 64	6	-0.8735	0.7630	0.7039	-3.589	0.05
58	I 64	4	-0.6128	0.3755	0.0633	-1.097	0.35
59	I 65(s)	4	-0.9131	0.8337	0.7506	-3.167	0.10
60	SR 67	6	-0.8113	0.6582	0.4303	-2.775	0.05
61	SR 75	4	-0.9475	0.8978	0.8467	-4.192	0.10
62	SR 135	6	-0.8989	0.8080	0.7600	-4.103	0.05
63	US 150	2	-1.0000	1.0000	----	----	----
64	US 231(n)	6	-0.7488	0.5607	0.4509	-2.260	0.10
65	US 231(s)	6	-0.8611	0.7415	0.6769	-3.387	0.05
66	SR 234	6	-0.8395	0.7048	0.6310	-3.090	0.05
67	SR 236	4	-0.8726	0.7614	0.6421	-2.526	0.15
68	US 421(n)	6	-0.7923	0.6277	0.5346	-2.597	0.10
69	US 421(s)	3	-0.8231	0.6775	0.3550	-1.449	0.35

Table A.3 Pavement Characteristics Data for Rigid Pavements in Indiana

S/No	Highway Route	Location (miles)	Pavement Age (yr.)	Pavement SN	Mean AADT	Cumulative ESAL
1	I-94	264	14.84	10.00	50,099	32,870,000
2	I-65	192	13.43	10.00	26,853	22,770,000
3	I-69	200	19.10	10.00	17,643	14,900,000
4	I-70	130	16.17	10.00	27,989	20,010,000
5	I-74	135	20.18	10.00	10,516	9,380,000
6	I-64	30	13.44	10.00	10,636	6,320,000

Table A.4 Pavement Characteristics Data for Flexible Pavements in Indiana

S/No	Highway Route	Location (miles)	Pavement Age (yr.)	Pavement SN	Mean AADT	Cumulative ESAL
1	SR 1(n)	217	10.12	5.05	1594	108,000
2	SR 1(s)	116	12.17	4.92	1320	113,500
3	SR 2	259	6.54	5.47	3753	116,500
4	SR 3(n)	200	9.48	5.09	2913	186,500
5	SR 3(s)	83	7.73	5.29	1863	98,000
6	SR 4	257	10.16	4.72	1163	80,000
7	SR 5	232	8.93	4.76	1030	62,000
8	US 6	249	7.56	5.59	2999	153,000
9	SR 8	248	7.95	5.00	1075	57,500
10	SR 9(n)	223	13.18	5.14	3010	278,000
11	SR 9(s)	117	9.20	4.94	2067	128,500
12	SR 10	236	5.95	5.04	902	36,500
13	SR 13	208	7.72	5.51	1711	89,000
14	SR 14	223	13.20	4.63	1110	99,000
15	SR 16	212	6.81	4.74	384	18,500
16	SR 17	229	6.29	4.99	898	38,000
17	SR 18	193	15.95	5.43	1453	156,500
18	SR 19	216	7.17	5.34	1980	96,000
19	US 20	268	8.76	5.32	3689	218,000
20	SR 23	261	3.82	5.29	1850	47,500
21	US 24	214	9.66	5.57	4222	275,500
22	SR 25	202	7.25	5.32	2341	114,500
23	SR 26	180	7.42	5.17	1406	75,500
24	SR 28	175	9.11	5.54	1737	107,000
25	SR 29	191	6.79	6.21	1991	89,000

Table A.4 (continued)

S/No	Highway Route	Location (miles)	Pavement Age (yr.)	Pavement SN	Mean AADT	Cumulative ESAL
26	US 30	242	12.63	5.48	8351	712,000
27	US 31(n)	204	7.04	5.16	7579	360,000
28	US 31(s)	91	7.68	5.68	2535	131,500
29	SR 32	163	8.69	5.15	2248	132,000
30	SR 33	244	11.07	5.42	3456	295,500
31	US 35	206	9.33	6.54	3339	210,500
32	US 36	147	6.94	5.64	1955	91,500
33	SR 37(n)	203	10.85	5.99	4853	355,500
34	SR 37(s)	48	5.53	5.18	2595	97,000
35	SR 38	157	12.43	4.93	1496	125,500
36	SR 39(n)	212	8.68	5.28	1357	79,500
37	SR 39(s)	102	9.73	4.86	850	56,000
38	US 40	139	8.79	5.49	4828	287,000
39	US 41	74	7.60	5.29	5625	289,000
40	SR 42	122	14.22	4.30	605	58,000
41	SR 43(n)	194	10.27	5.37	2416	167,500
42	SR 43(s)	92	15.83	4.56	332	35,500
43	SR 44	125	6.67	5.10	1768	79,500
44	SR 46	105	10.82	4.89	2222	162,500
45	SR 47	160	14.49	4.92	834	82,000
46	SR 48	99	8.95	4.67	563	34,000
47	US 50	82	7.61	5.53	3041	156,500
48	US 52(n)	163	12.25	5.25	4730	195,500
49	US 52(s)	113	7.28	5.27	1380	68,000
50	SR 55	200	16.18	4.83	1066	116,500

Table A.4 (continued)

S/No	Highway Route	Location (miles)	Pavement Age (yr.)	Pavement SN	Mean AADT	Cumulative ESAL
51	SR 56	62	11.21	4.87	1431	108,500
52	SR 57	55	7.12	5.37	2458	118,000
53	SR 58	76	4.42	5.41	848	25,500
54	SR 60	57	9.19	5.12	2467	153,000
55	SR 62	34	6.98	5.03	2833	133,500
56	SR 63	131	7.75	5.09	2221	116,000
57	SR 64	40	7.82	4.81	2024	107,000
58	I 64	27	9.79	5.10	6835	2,660,000
59	I 65(s)	79	5.45	5.91	11994	2,480,000
60	SR 67	128	7.47	5.38	3500	176,500
61	SR 75	165	11.08	4.23	560	42,000
62	SR 135	67	8.86	4.55	1728	103,000
63	US 150	53	10.24	5.19	1708	118,000
64	US 231(n)	196	10.44	5.12	2600	183,500
65	US 231(s)	69	9.02	5.84	2328	142,000
66	SR 234	150	11.72	4.95	508	40,000
67	SR 236	141	13.11	4.87	491	43,500
68	US 421(n)	195	9.22	5.12	2017	125,500
69	US 421(s)	98	10.98	5.24	1937	143,500

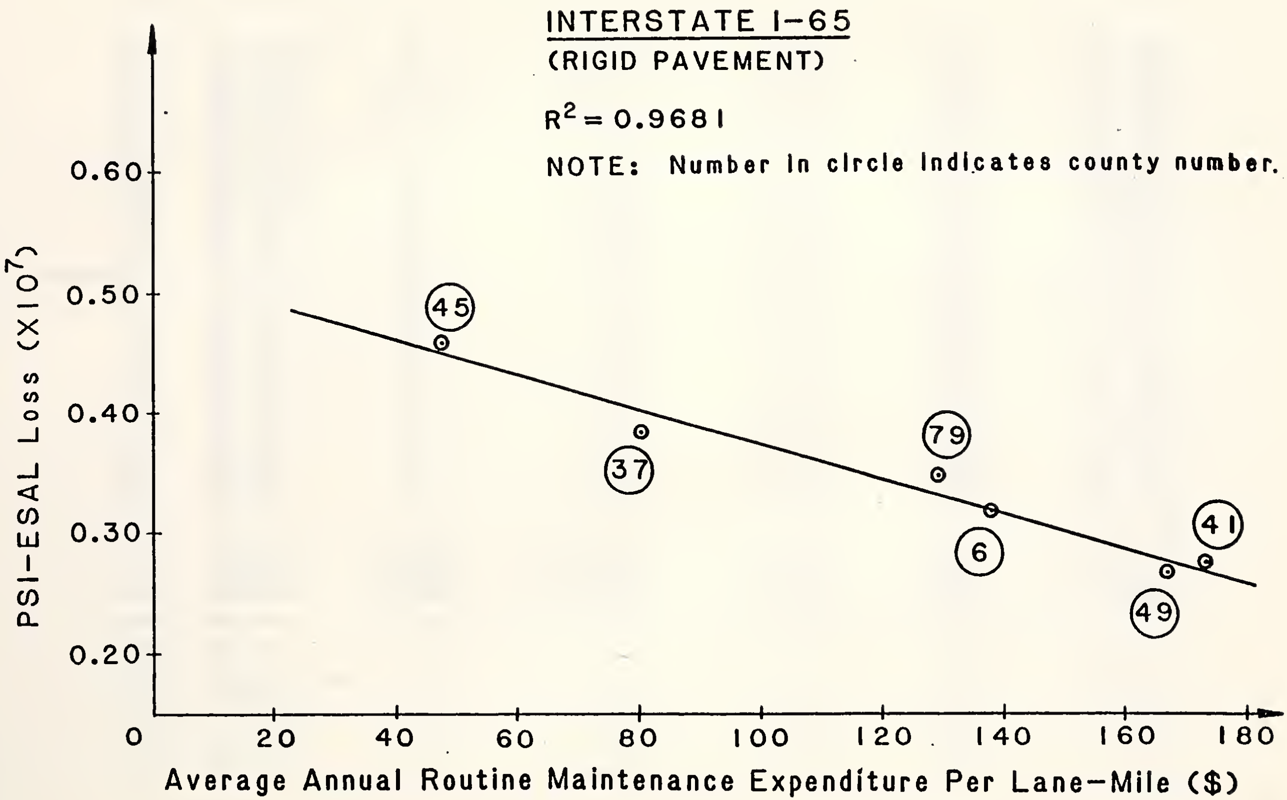

Figure A.1 PSI-ESAL Loss vs. Maintenance Expenditure Plot for I-65

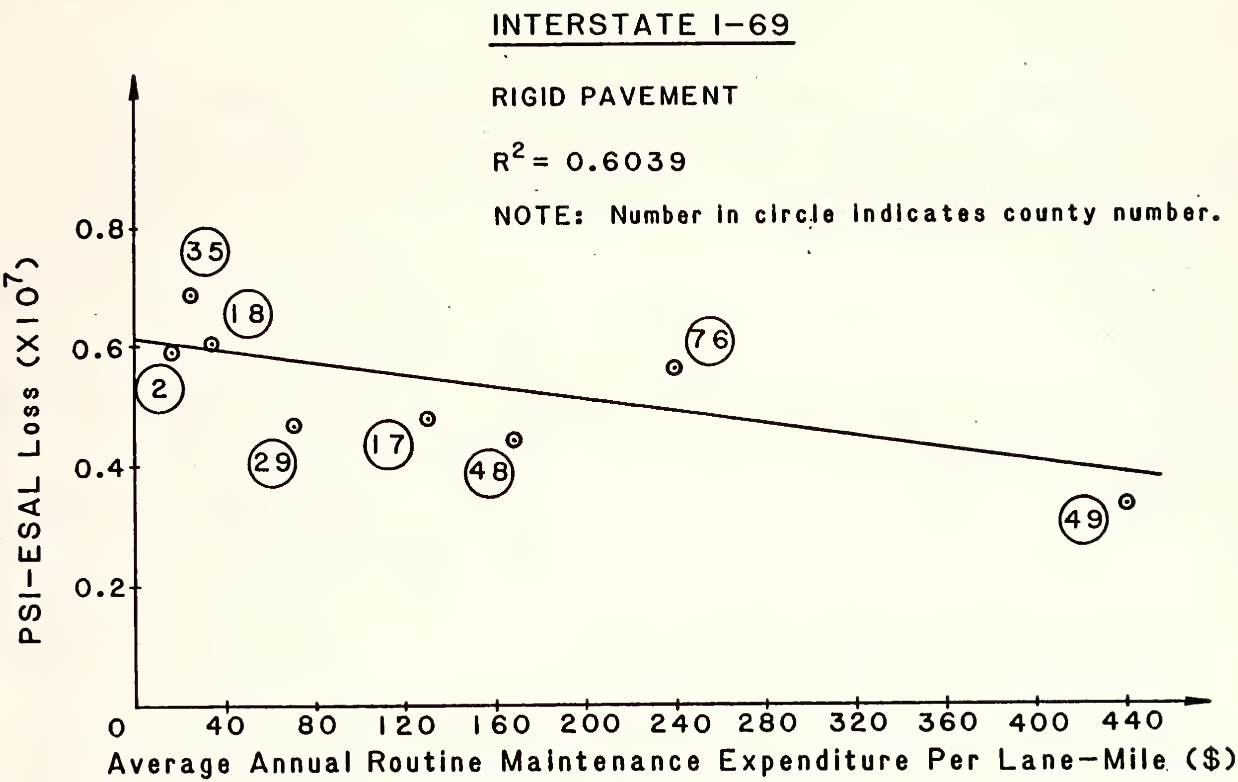

Figure A.2 PSI-ESAL Loss vs. Maintenance Expenditure Plot for I-69

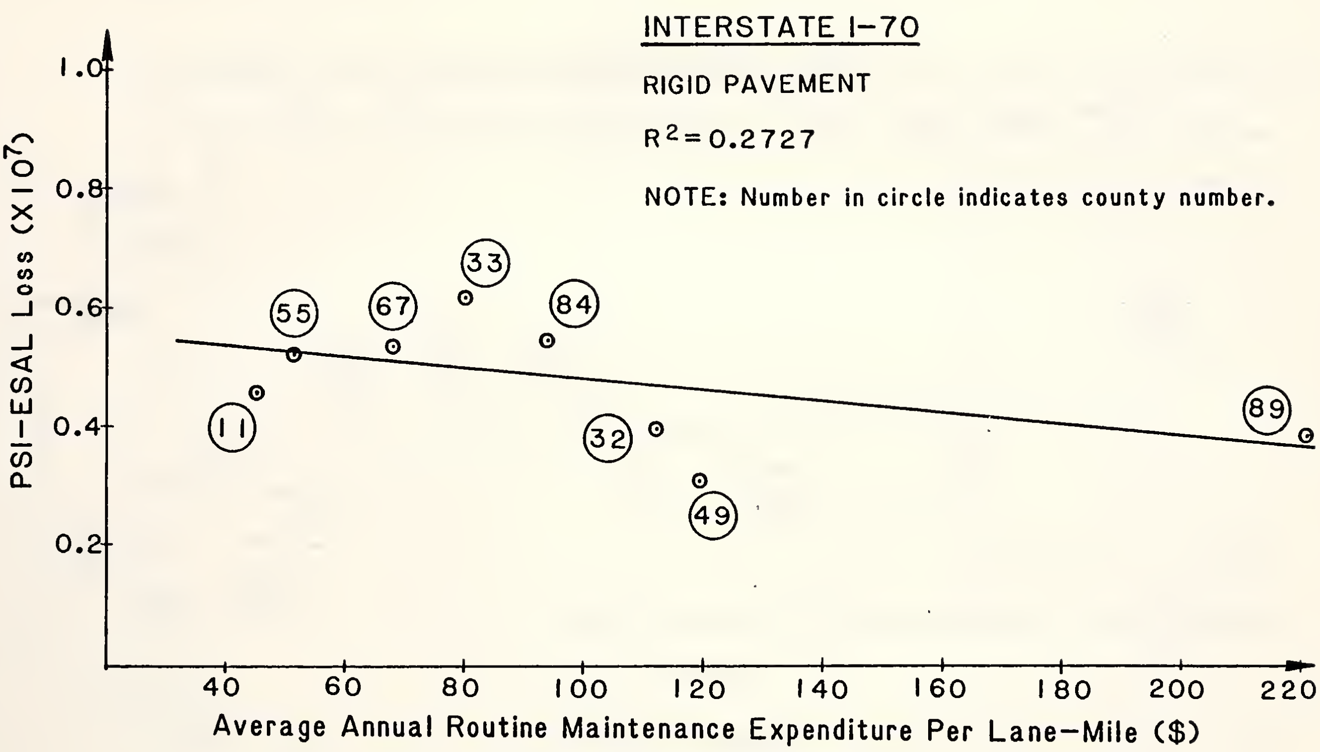

Figure A.3 PSI-ESAL Loss vs. Maintenance Expenditure Plot for I-70

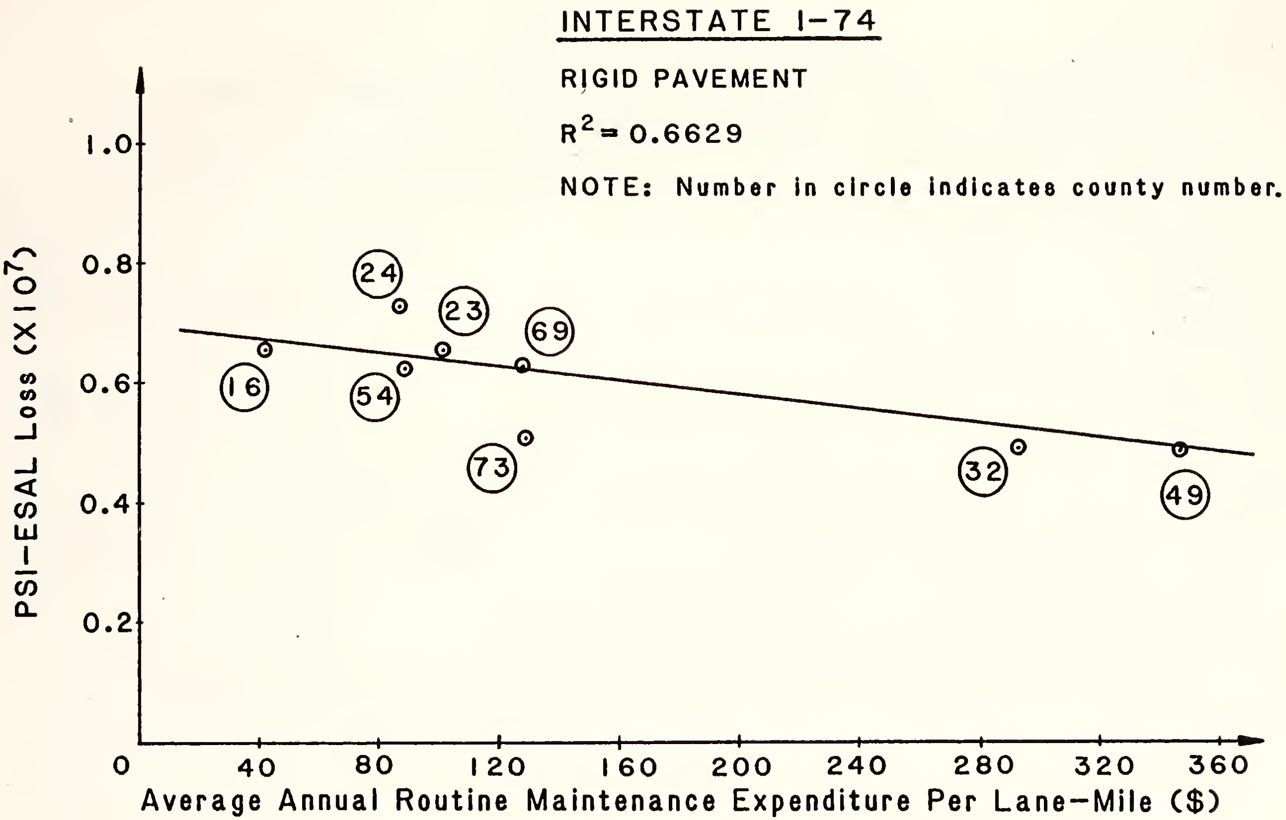

Figure A.4 PSI-ESAL Loss vs. Maintenance Expenditure Plot for I-74

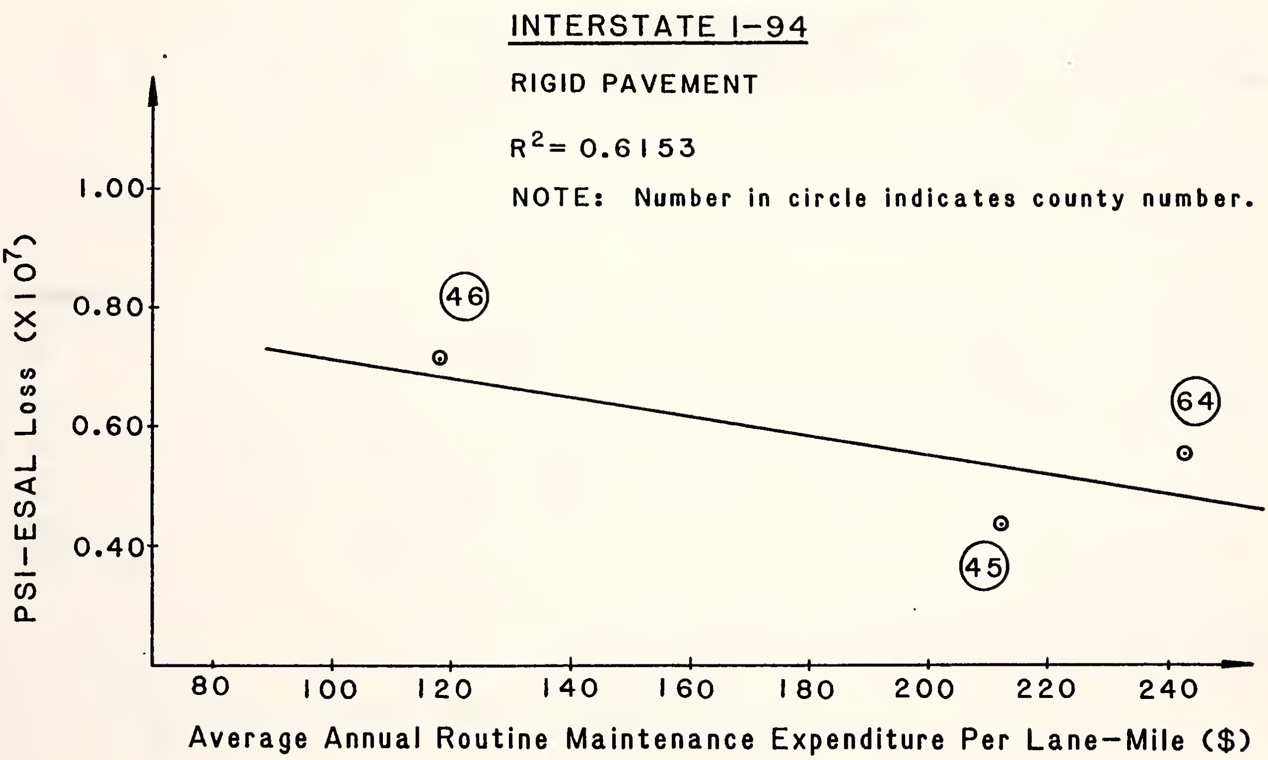

Figure A.5 PSI-ESAL Loss vs. Maintenance Expenditure Plot for I-94

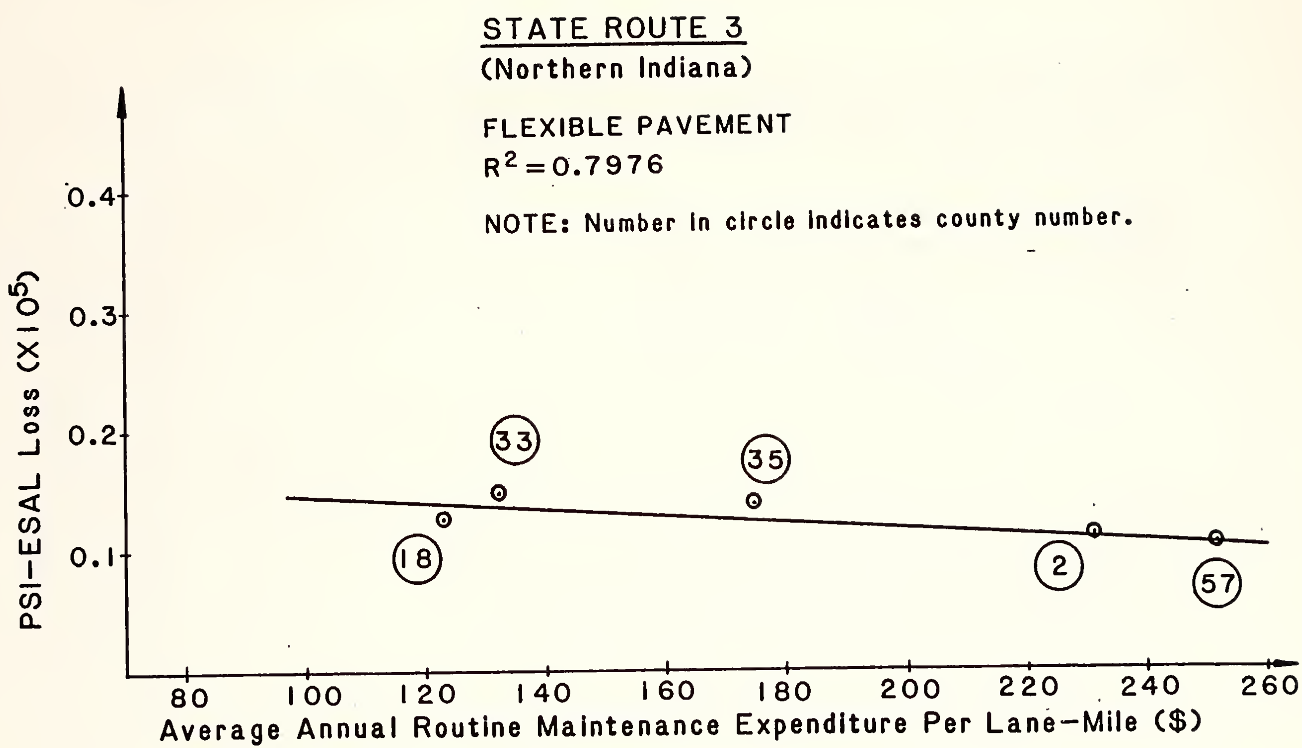

Figure A.6 PSI-ESAL Loss vs. Maintenance Expenditure Plot for SR 3n

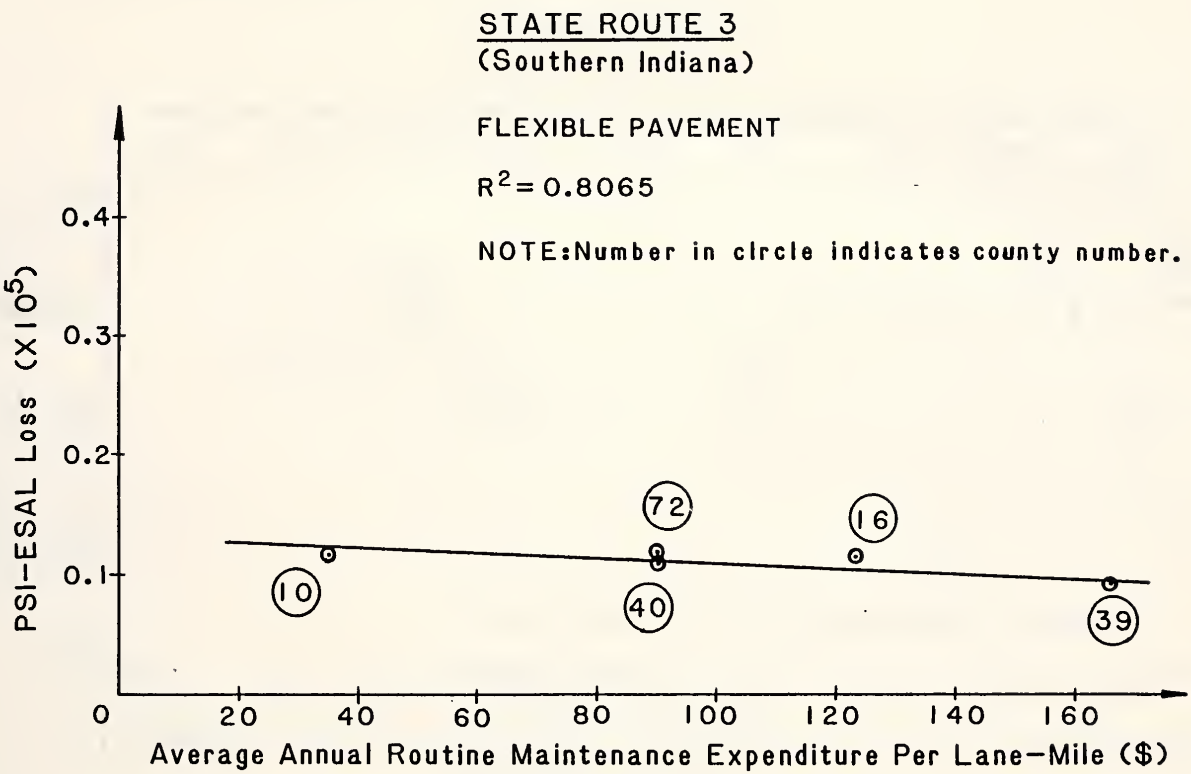

Figure A.7 PSI-ESAL Loss vs. Maintenance Expenditure Plot for SR 3s

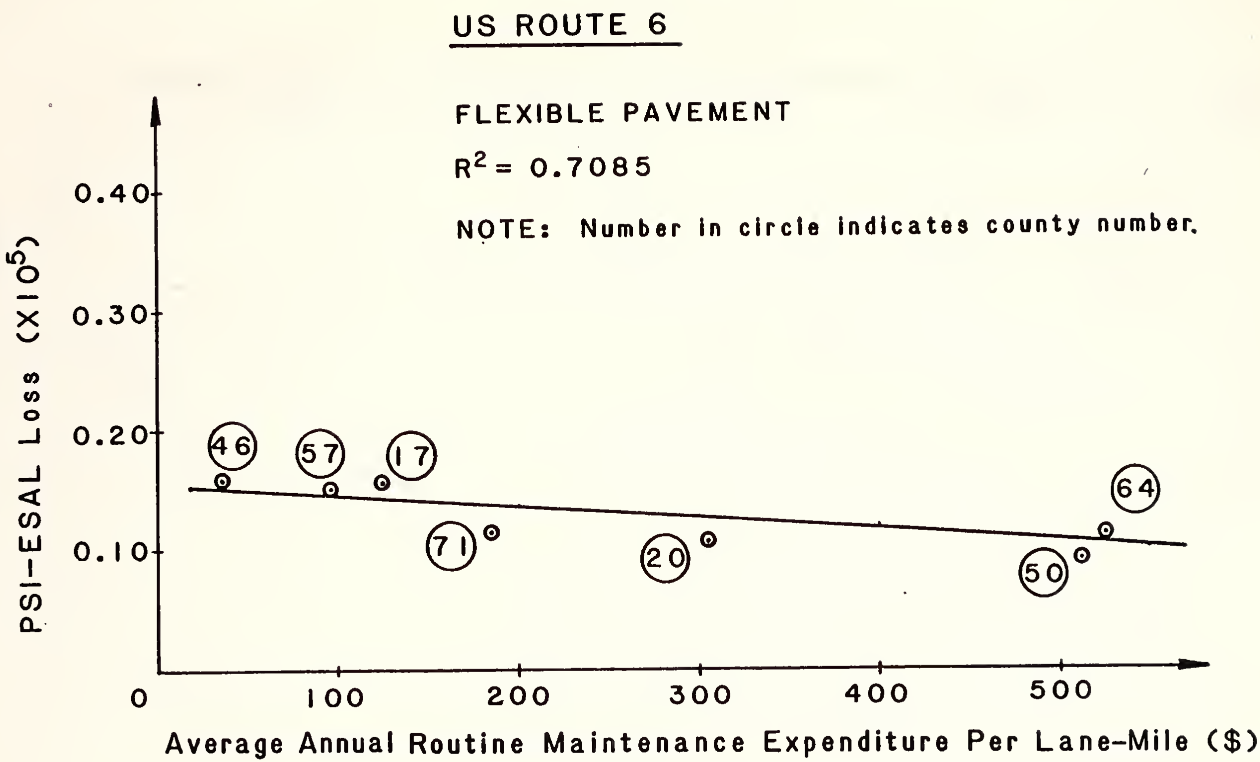

Figure A.8 PSI-ESAL Loss vs. Maintenance Expenditure Plot for US 6

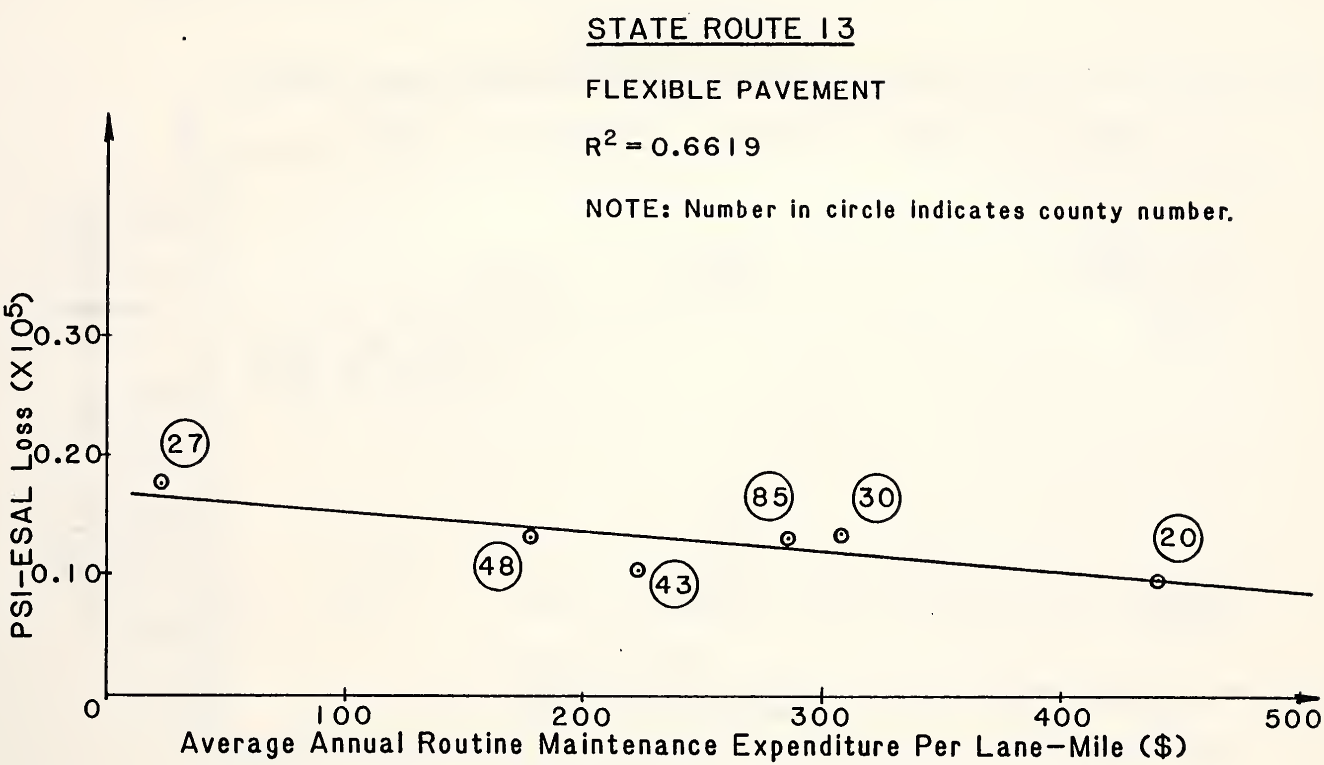

Figure A.9 PSI-ESAL Loss vs. Maintenance Expenditure Plot for SR 13

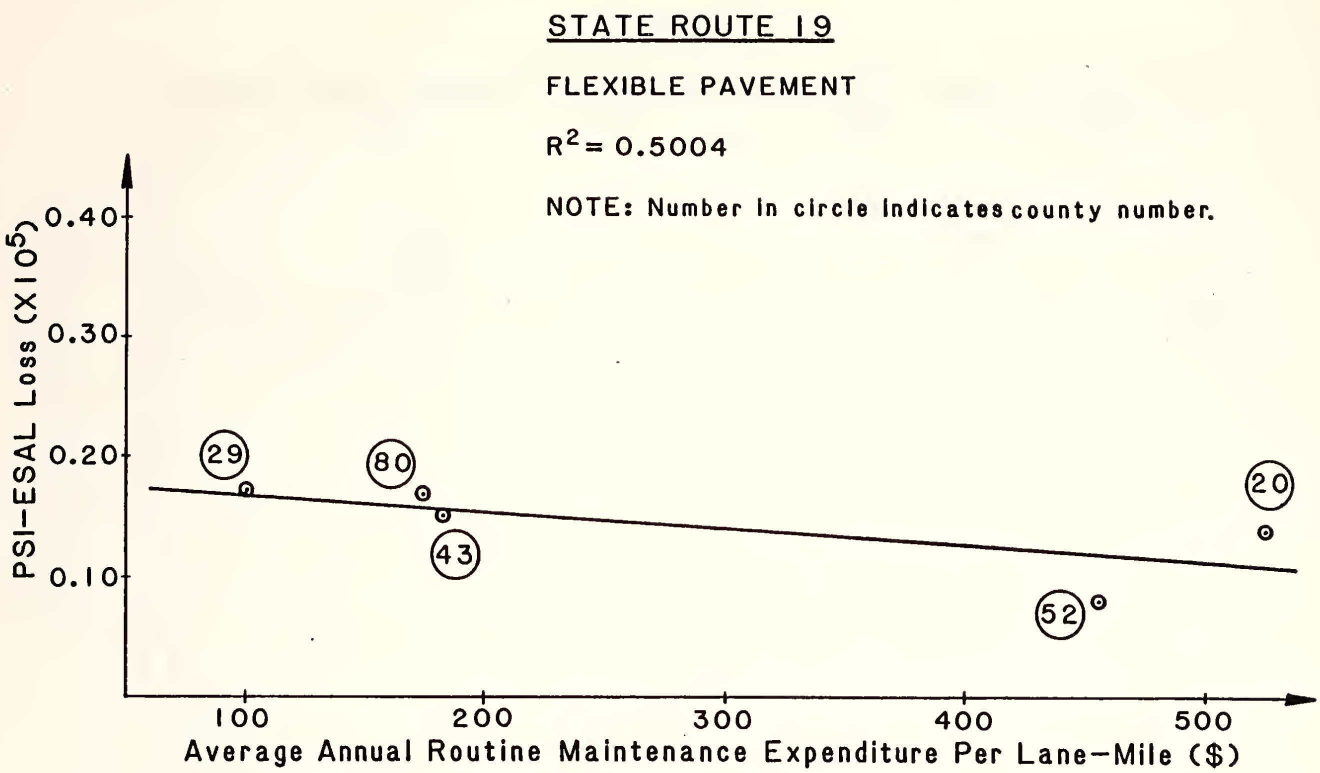

Figure A.10 PSI-ESAL Loss vs. Maintenance Expenditure Plot for SR 19

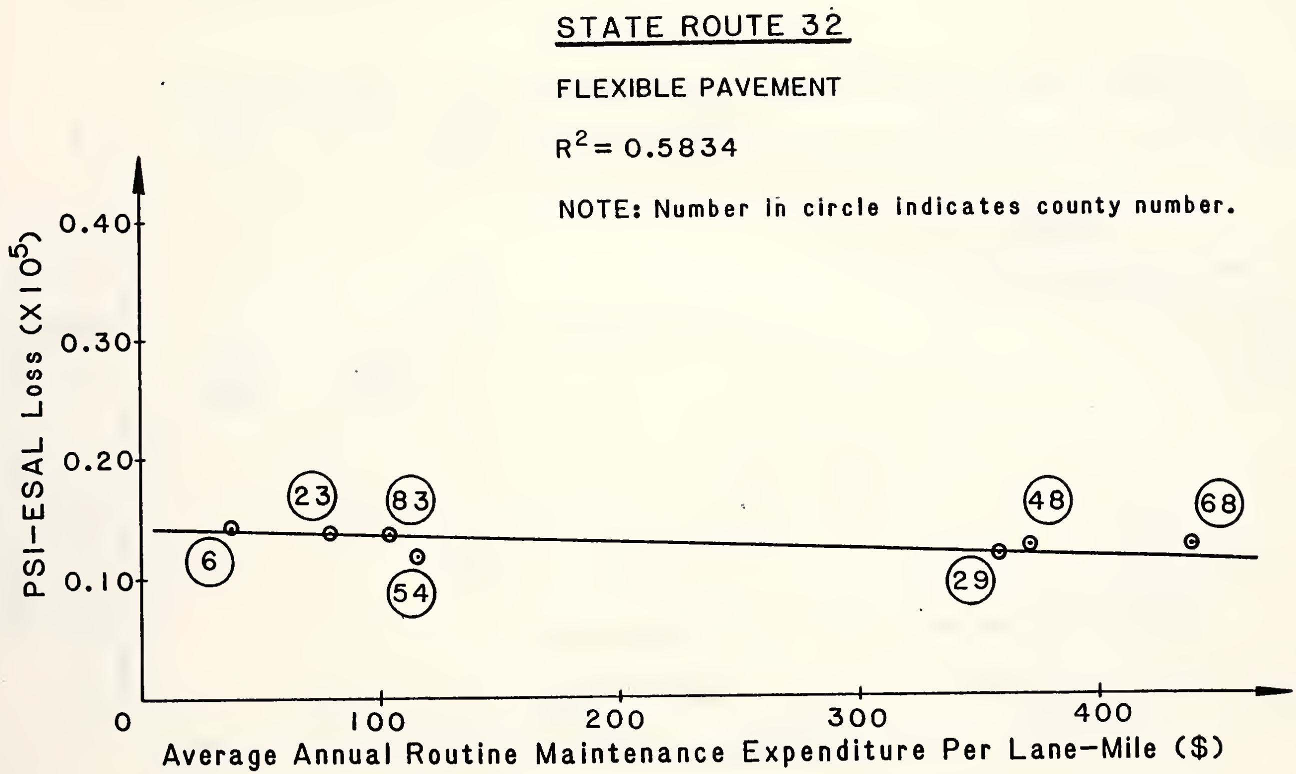

Figure A.11 PSI-ESAL Loss vs. Maintenance Expenditure Plot for SR 32

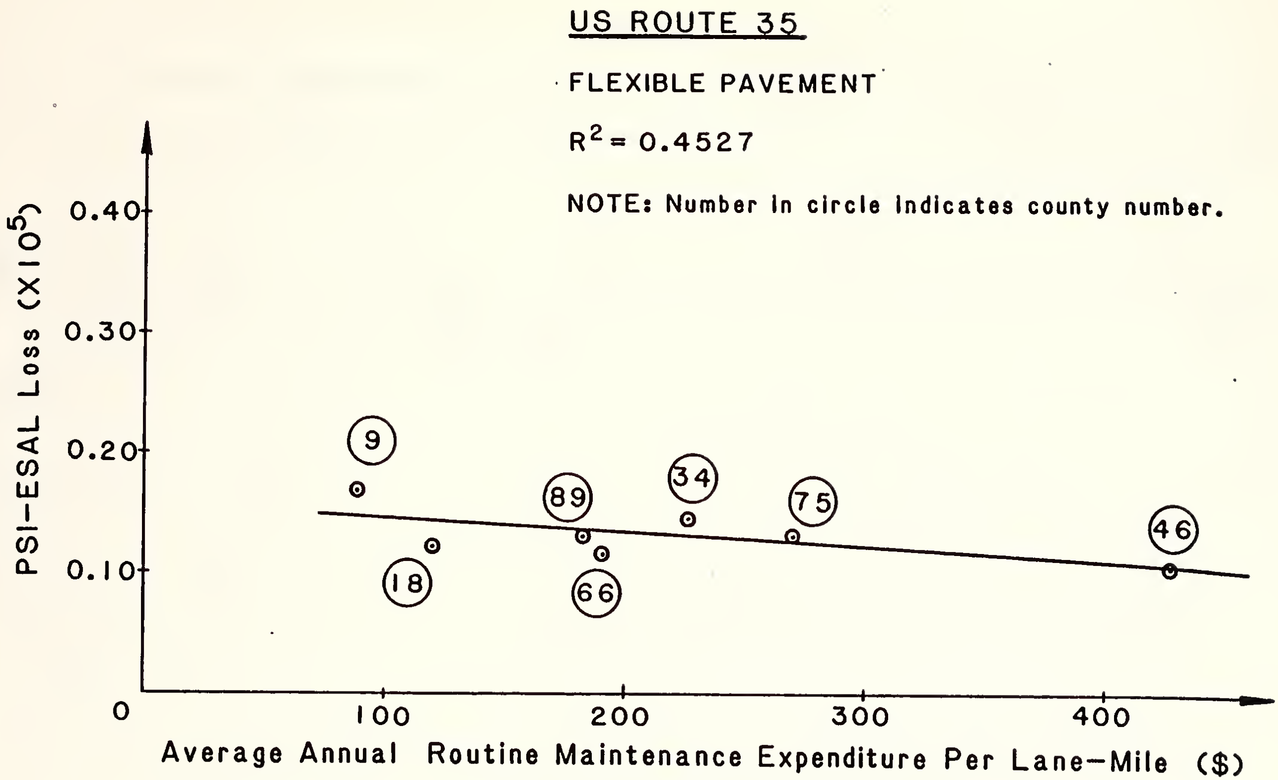

Figure A.12 PSI-ESAL Loss vs. Maintenance Expenditure Plot for US 35

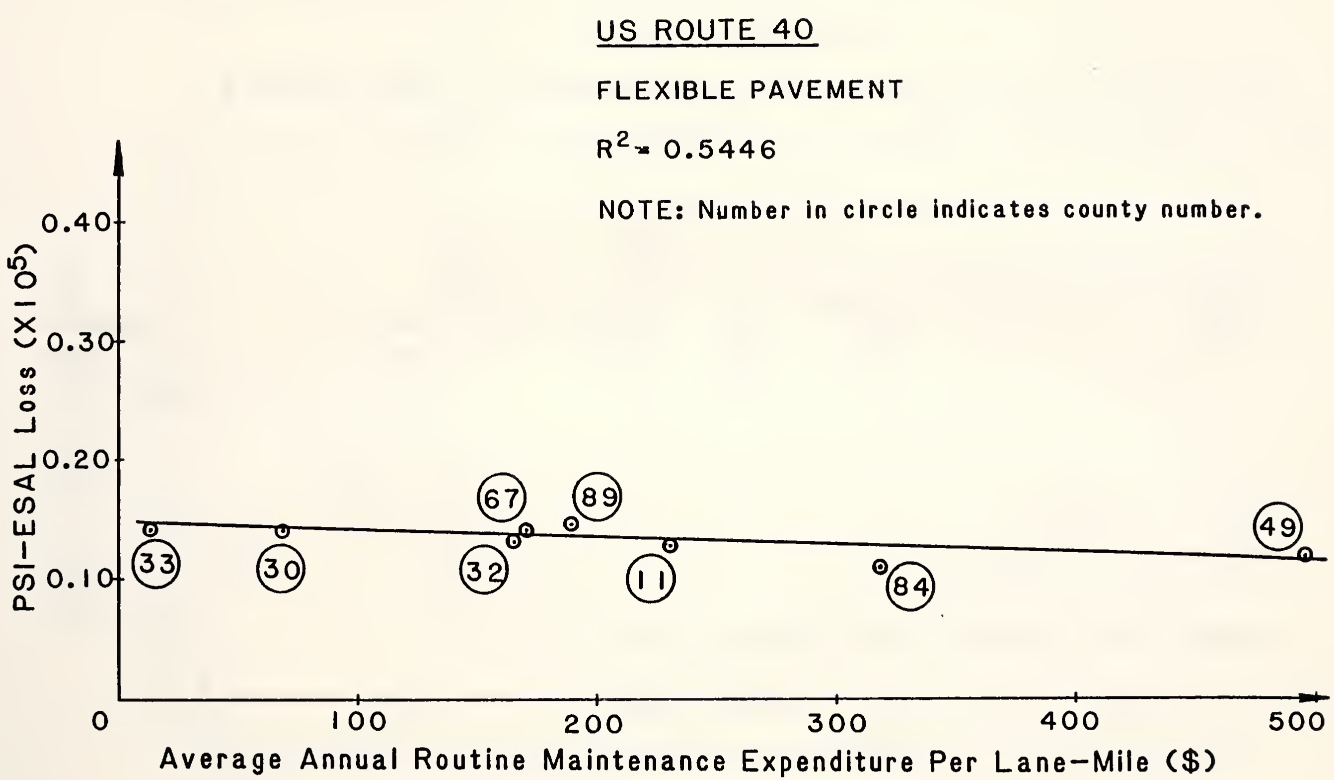

Figure A.13 PSI-ESAL Loss vs. Maintenance Expenditure Plot for US 40

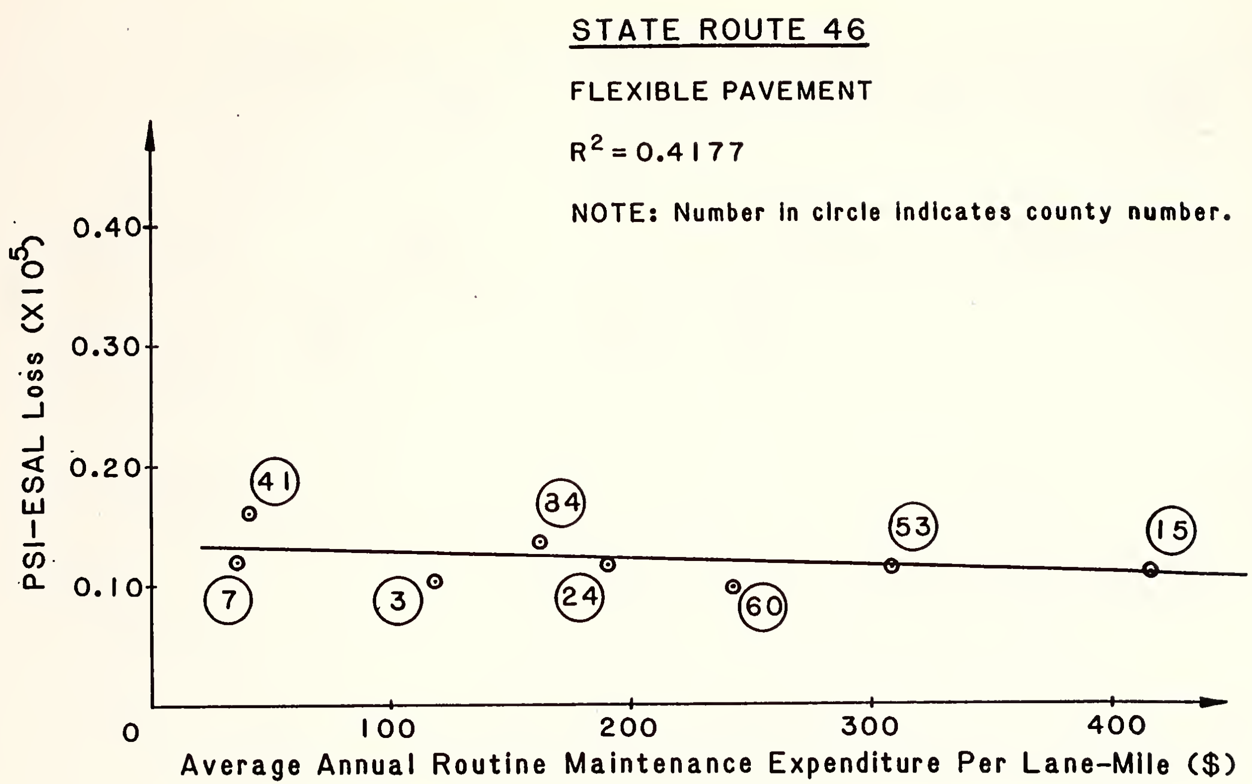

Figure A.14 PSI-ESAL Loss vs. Maintenance Expenditure Plot for SR 46

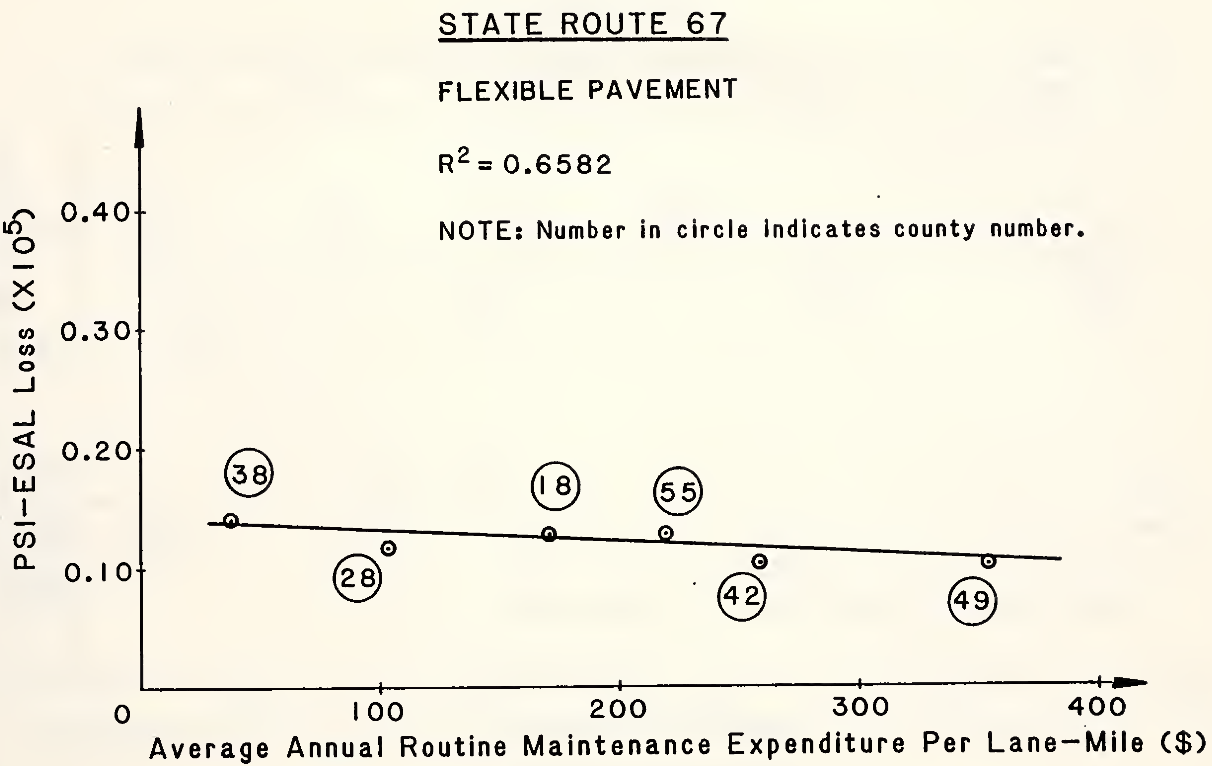

Figure A.15 PSI-ESAL Loss vs. Maintenance Expenditure Plot for SR 67

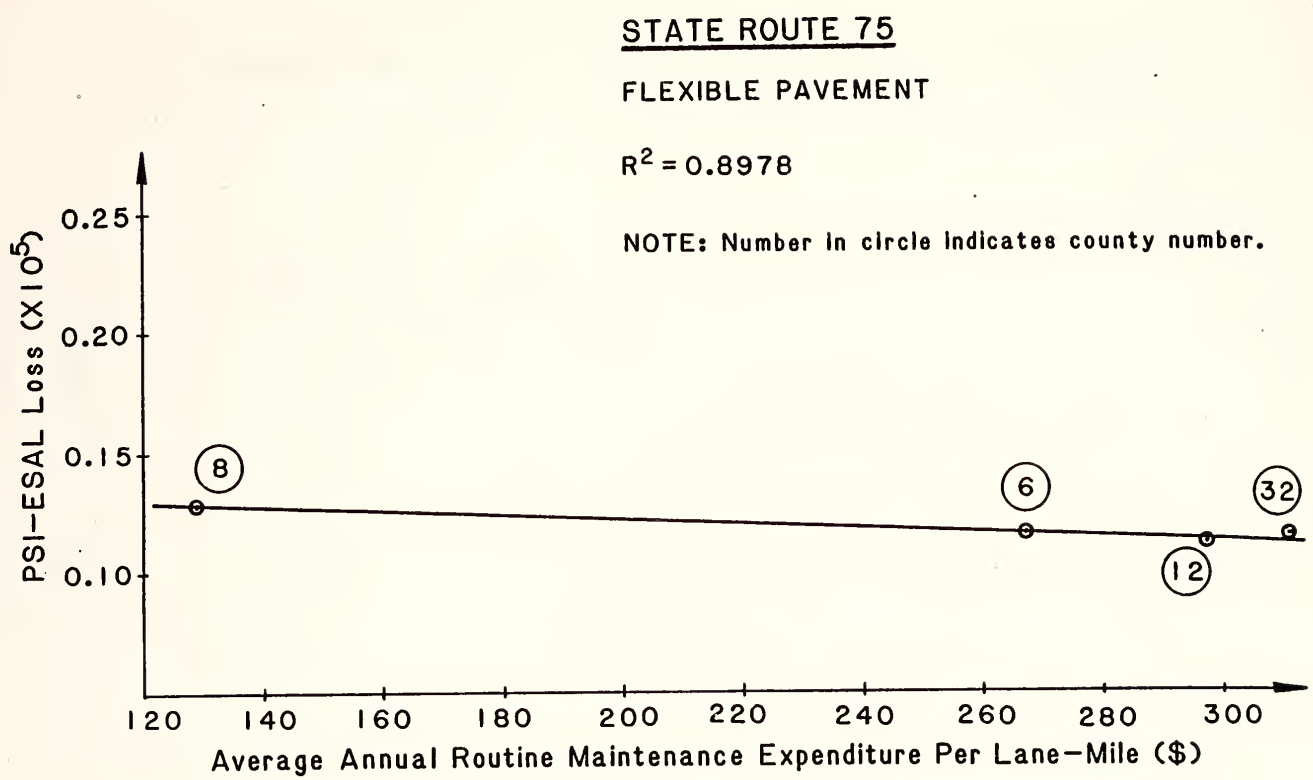

Figure A.16 PSI-ESAL Loss vs. Maintenance Expenditure Plot for SR 75

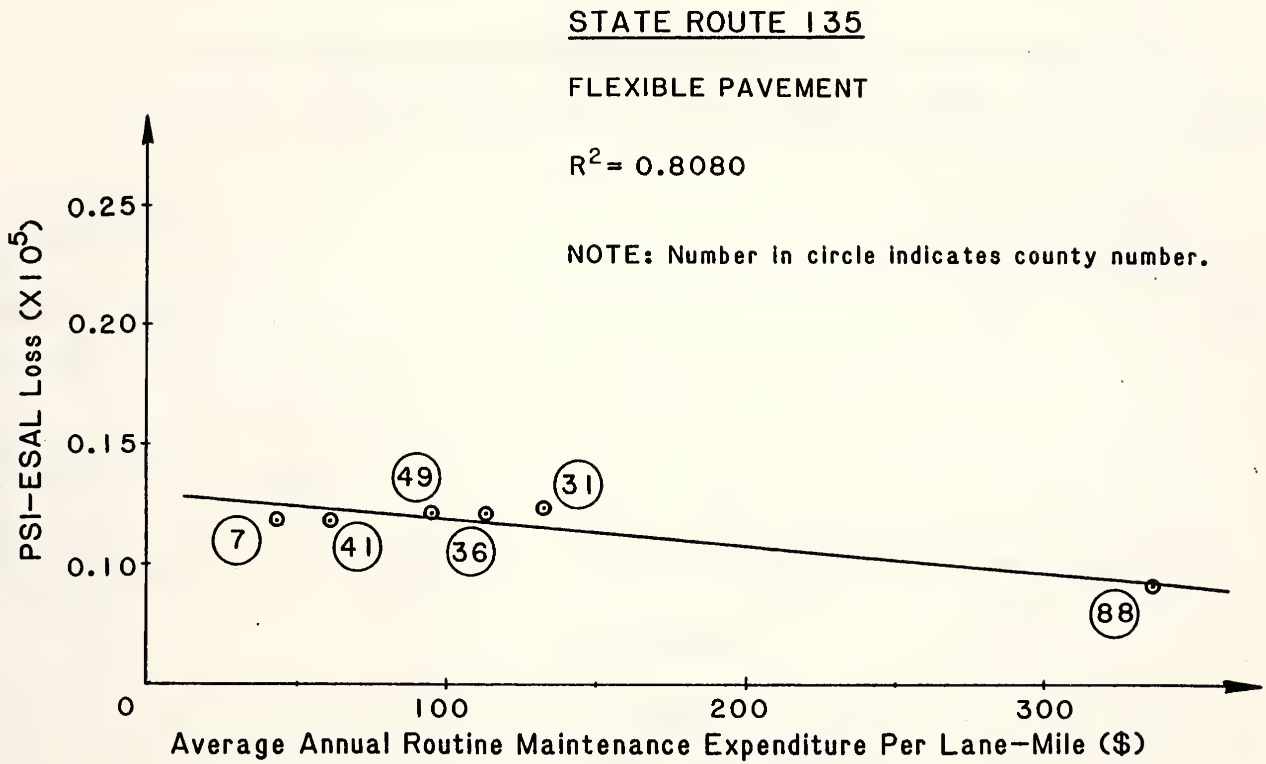

Figure A.17. PSI-ESAL Loss vs. Maintenance Expenditure Plot for SR 135

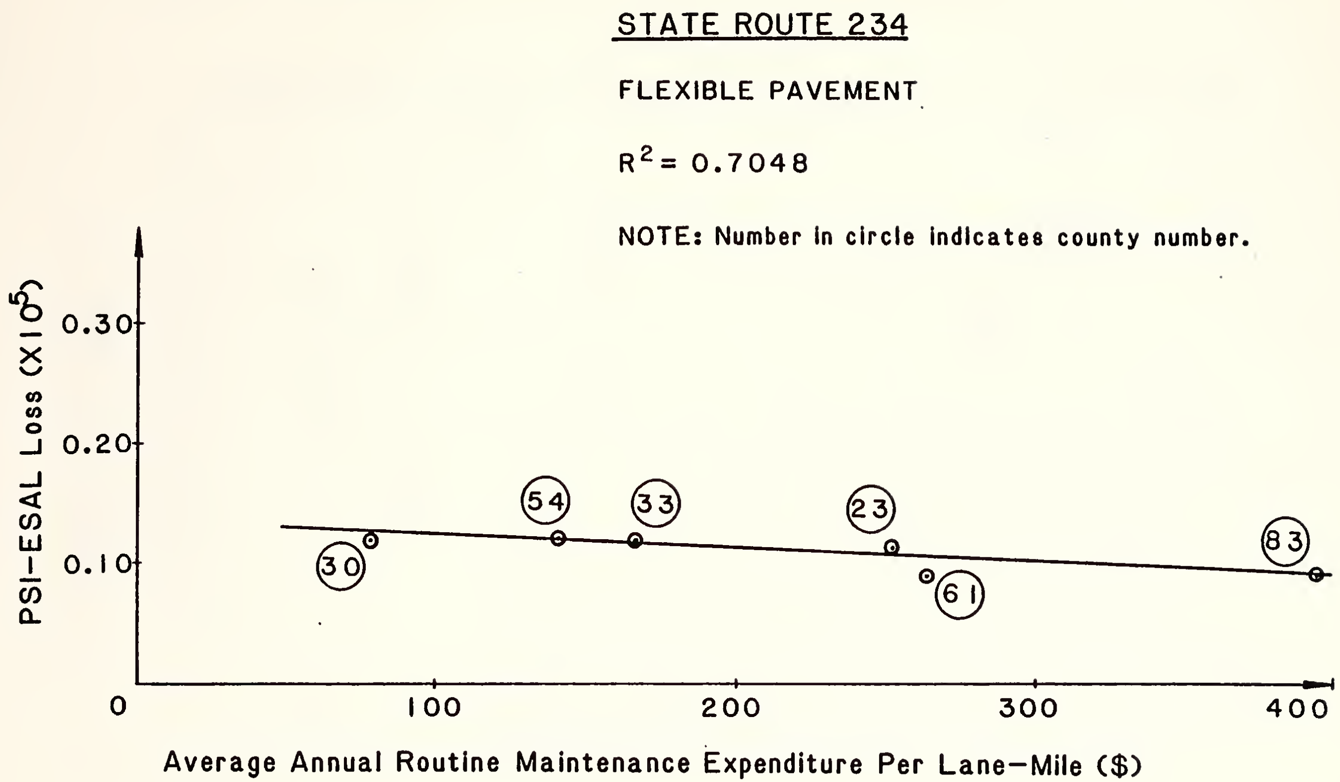

Figure A.18 PSI-ESAL Loss vs. Maintenance Expenditure Plot for SR 234

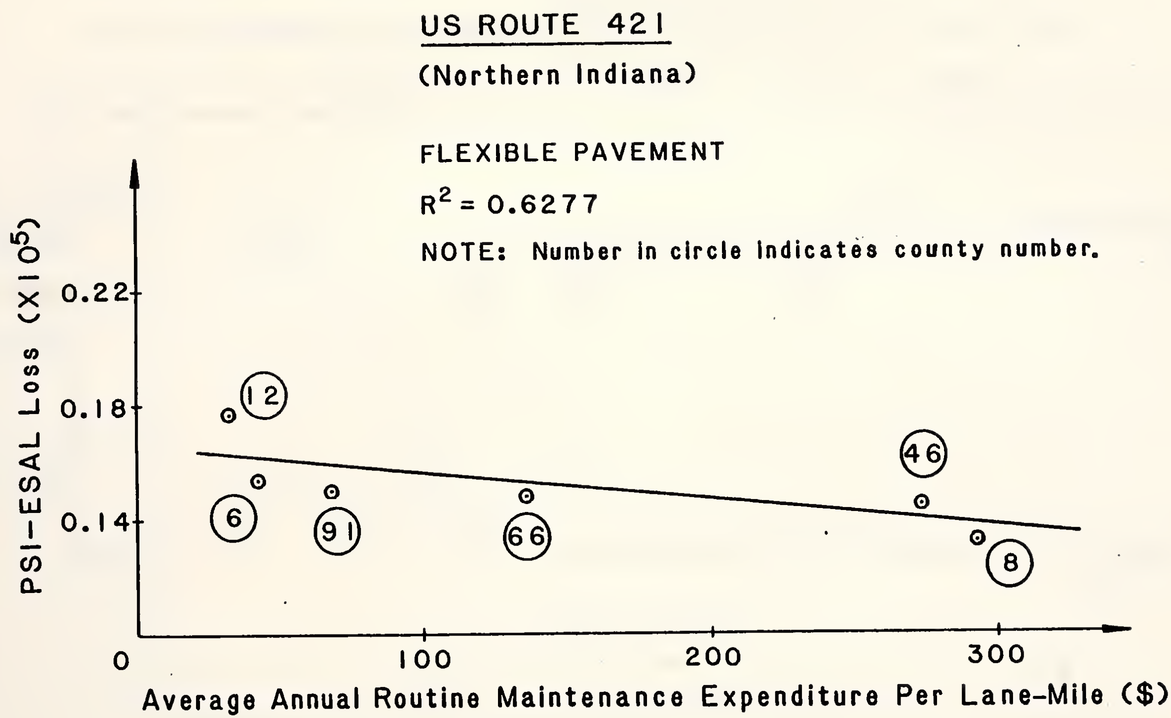

Figure A.19 PSI-ESAL Loss vs. Maintenance Expenditure Plot for US 421n

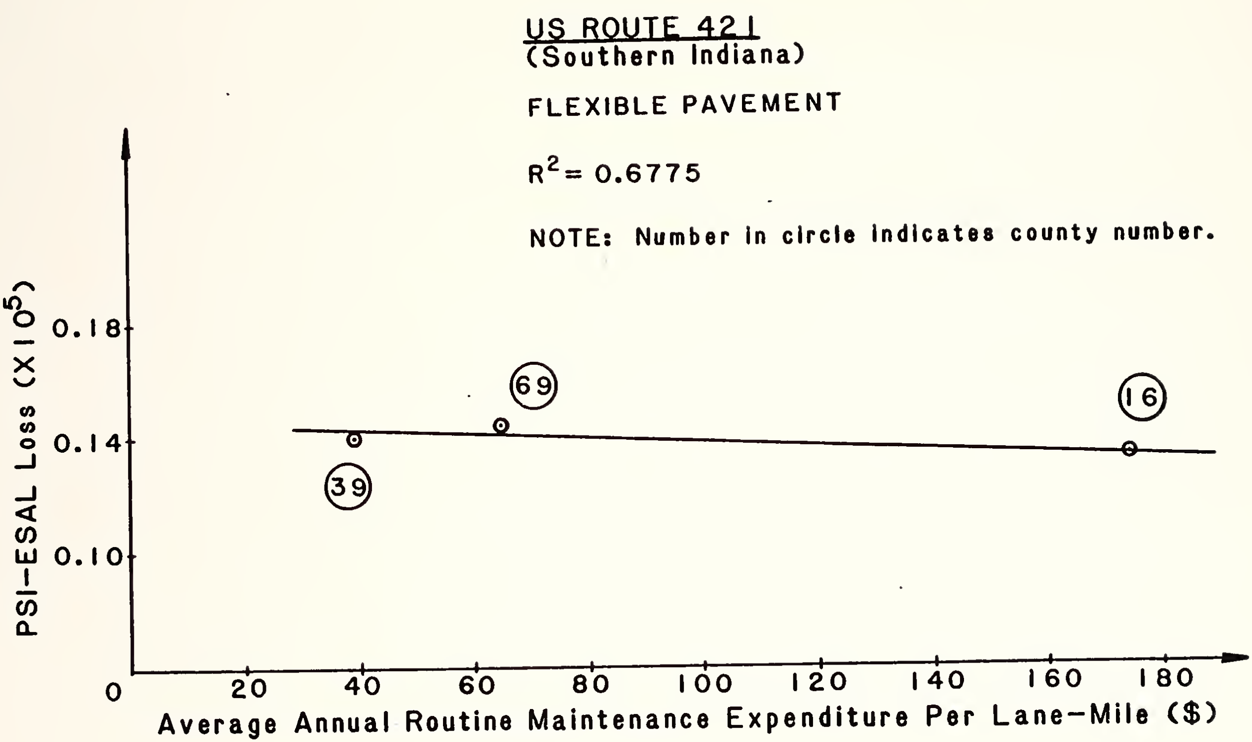

Figure A.20 PSI-ESAL Loss vs. Maintenance Expenditure Plot for US 421s

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